ASD-TR-76-7

MICROWAVE LANDING SYSTEM UTILIZATION AND CONVENTIONAL AVIONICS

HUMAN FACTORS BRANCH
CREW EQUIPMENT AND HUMAN FACTORS DIVISION

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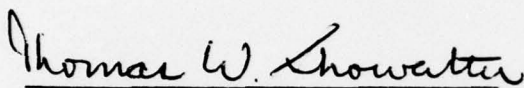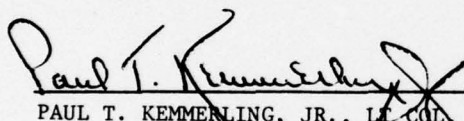
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The study examined the effects of flying different microwave landing system approach profile designs with various types of conventional avionics. All the conventional systems used possessed similar limitations in that they were unable to present course guidance throughout the microwave landing system profiles. The loss of course guidance adversely affected pilot performance and, on occasion, made for unsafe conditions.

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FOREWORD

The work reported was performed at the Crew Station Design Facility (CSDF), Crew Station, Escape, and Human Factors Branch of the Aeronautical Systems Division, Wright-Patterson AFB, Ohio. The effort covered in this report was accomplished during the period 15 August through 1 November 74. Mr. Richard Geiselhart was the CSDF director during the program. Capt. Thomas W. Showalter was the contributing author.

Acknowledgement is given the Air Force Flight Dynamics Laboratory (AFFDL), who sponsored the research and provided for the operation and maintenance of the CSDF under contract F33615-74-C-3052 during the period covered in the report. The Singer Company, Simulation Products Division, Binghampton, New York was the operation and maintenance contractor.

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INTRODUCTION

The Air Force Flight Dynamics Laboratory (AFFDL) is conducting an investigation of the Microwave Landing System (MLS). The MLS presents a precise high energy signal that is capable of creating a large wedge of electronically defined airspace. The signal's high energy characteristics make wave distortion due to terrain, buildings, and aircraft difficult and offers the potential for reliable accurate guidance close to touchdown (TD). The signal extends laterally to 60° either side of the runway centerline extended, vertically up to 20°, and longitudinally out to a radius of 20 miles. Within this area MLS provides precise distance, azimuth angle, and elevation angle information, which will permit the construction of curved/segmented approach profiles in the terminal area. Previously, approach profiles were designed to track a beam that guided the aircraft through the terminal navigation area on a course coinciding with the runway centerline and on a glide path of a constant elevation angle terminating at TD. With MLS the capability now exists to safely increase air traffic density in the terminal area and to increase runway utilization. This can be done without increasing the workload of an air-traffic controller since airborne MLS equipment will permit the pilot to perform a large share of the terminal area navigation. Aircraft will fly on radar monitored approaches instead of the present radar controlled approaches. MLS ground stations are small, relatively lightweight, and hence portable. They would be useful in military operations. With the use of portable MLS transmitters a newly established airfield would be able to provide approach guidance. The airfield, once its usefulness had ended, could be dismantled quickly and easily   established in another more strategic location. In essence, MLS may be offering aviation the opportunity to more efficiently use airspace and airfields.

MLS testing deals with a variety of issues. Determining the quality of the electronic signal and mating ground stations with airborne receivers are primarily technical issues. Given that they are resolved, a set of operational issues will still need definition and resolution, which is the purpose of the Flight Profile Investigation (FPI). It will deal with problems like choosing safe, easily flown curved/segmented approaches and discovering the information needs of a pilot flying MLS approaches. The FPI has been divided into flight test and simulator test programs. Flight test will be performed by Instrument Flight Center (IFC), Randolph AFB, Texas, personnel using T-39 aircraft and simulation testing will be done at the Crew Station Design Facility (CSDF), Wright-Patterson AFB, Ohio, employing CSDF personnel.

Two specific test objectives were established for CSDF by AFFDL personnel:

(1) Determine which of the profiles obtained from AFFDL personnel are feasible to fly using various levels of existing avionics.

(2) Establish what displays and aircraft controls are needed to fully utilize the curved/segmented approach path capabilities of MLS.

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To fully utilize the curved/segmented approach path capabilities of MLS requires the use of avionics innovations not yet available for testing. Phase II of simulation will examine this objective. Phase I of simulation deals with determining profile feasibility when conventional avionics are used.

Conventional avionics, which were designed to fly ILS approaches, are not equipped to fully itilize all the position information that MLS provides. The glide slope in MLS is no longer just a beam as it was with the ILS. Instead it contains a set of adjacent glide slope planes each of which intersects the runway at the touchdown point and extends out to the limit of coverage (Figure 1). Tracking on one of the glide slope planes is similar to tracking the ILS glide slope beam and can be done with conventional avionics. However, while on a MLS glide slope plane the aircraft's angle of descent may be a value other than the glide slope angle, if the aircraft were tracking a course nonparallel to the runway centerline course. For example, if an aircraft is on a course creating an intercept angle of 60° with the runway centerline course, then it will have a descent angle half that of the glide slope angle. One planning to intersect the runway centerline at 90° would have an angle of descent equal to 0°. Thus, while tracking on the glide slope plane, any change of course will concomitantly require a change in angle of descent. This will require power adjustments during turns to remain on glide slope at a constant airspeed. Different types of MLS approaches have been proposed. Some are planar approaches, which means that the entire approach is flown on only one glide slope plane. Others are multi-glide path approaches that require the pilot to tra glide slope planes. To generate glide path information for segments no   y existing glide slope plane requires the avionics to compute range   airspeed values, coordinates of the proposed glide path, and other fac   ot processed by conventional avionics.

Course guidance in the MLS environment is complex. The MLS lateral environment is a set of adjacent radials which emanates from the stop end of the runway and defines an area out to 60° either side of the extended runway centerline (Figure 2). Tracking on a radial is the same as tracking the localizer beam (LOC) during an ILS approach and can be done with conventional avionics. Any approach flown in the MLS environment other than a typical ILS approach would contain crossleg segments that traverse radials emitted from MLS transmitter. Receiving course guidance during crossleg portions would require the avionics to generate a path by computing range values, airspeed values, wind values, course coordinates, and a variety of other factors not computed by conventional avionics. Only angular deviation from the selected azimuth beam can be processed by conventional systems, which are thus restricted to providing course guidance only when the aircraft is tracking on one of the selected azimuth radials.

Conventional systems generally present either unprocessed information (raw data) or unprocessed and processed information (command). Both conventional systems have similar limitations in the MLS environment. They can provide glide slope information only when the aircraft is flying on the

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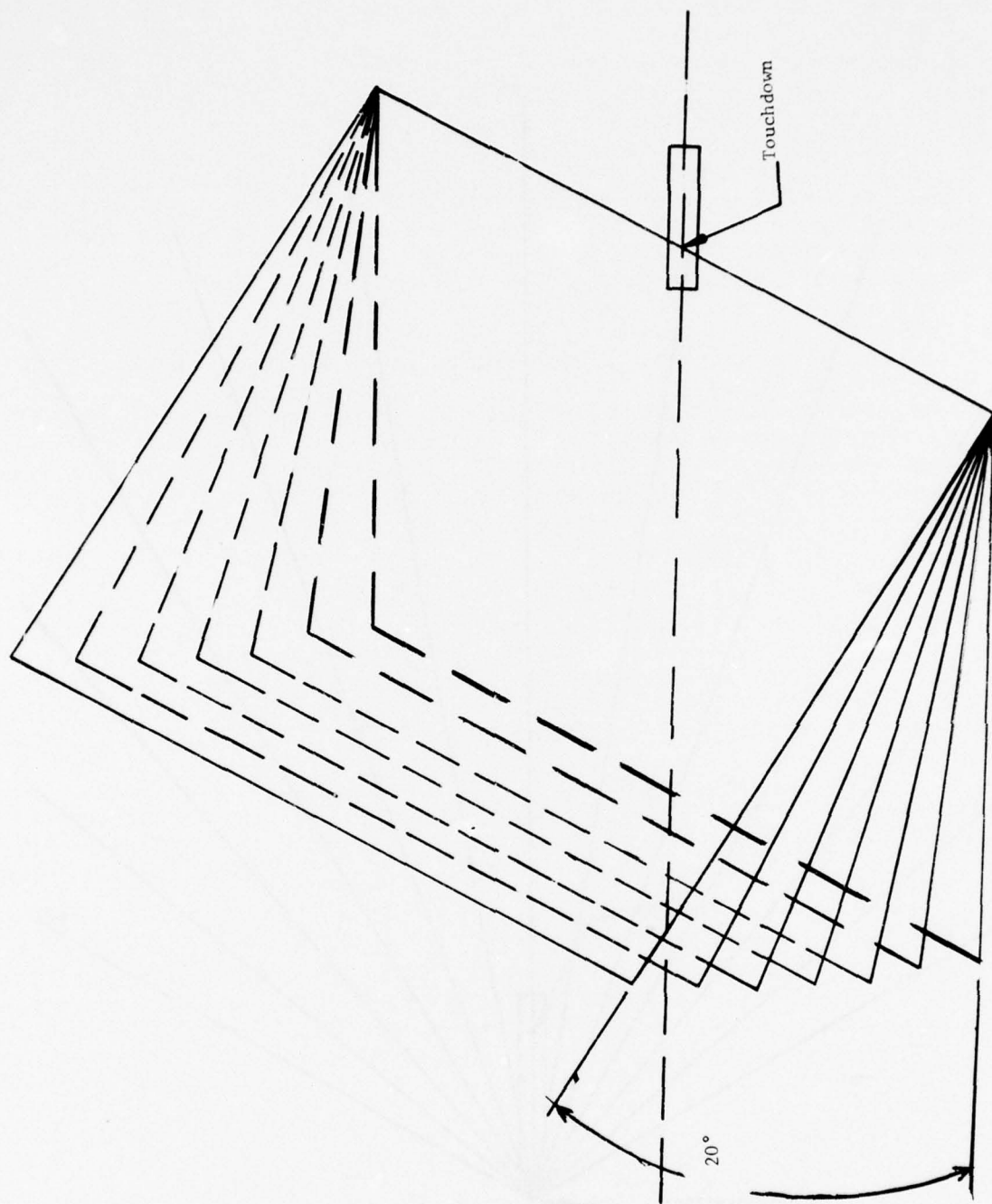
Figure 1.- MLS Vertical Geometry

20°

Touchdown

3
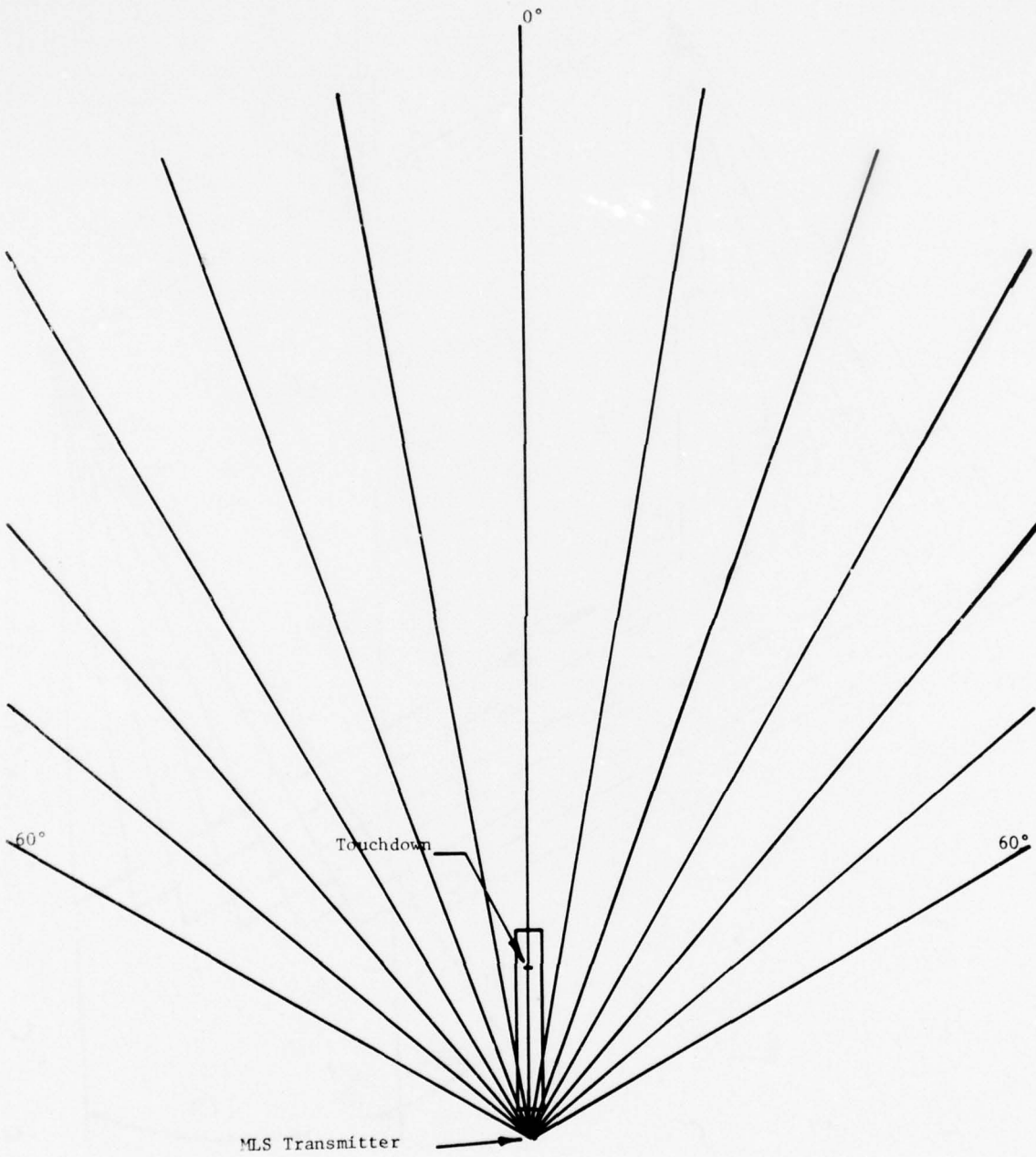
Figure 2

MLS Lateral
Geometry

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selected glide slope plane and they can give course information only when tracking the selected MLS radial. If the aircraft were to fly a multi-glide path approach, no glide path information would be presented during those approach portions not on one of the MLS glide slope planes. Similarly, if the aircraft were to traverse a set of radials, course information would be lost. In essence, when flying MLS curved/segmented approaches with conventional avionics, pilots generally lose course and/or glide slope information during some approach segments.

The conventional instrument systems for Phase I employed four systems which were: a system presenting unprocessed information (austere only), a system presenting both processed and unprocessed information (analog only), and two created by adding an Azimuth Angle Indicator (AAI) to each of the aforementioned systems (austere AAI, analog AAI). The AAI was a device included to cue the turn onto the runway centerline course. The Phase I analysis was divided into sub-phases, IA and IB, which incorporated essentially the same parameters but varied weather [no wind (IA) vs wind (IB)]. Only Phase IA will be reported at this time.

Phase IA profiles were defined in terms of intercept angle (45° vs 60°) and intercept distance from TD (2 NM. vs 4 NM.) and were planar, all being flown on a 2.5° glide slope plane. Figure 3, divided into parts A, B, C, and D, displays each of the Phase IA profiles. Each profile was composed if five segments; initial leg, turn 1, crossleg, turn 2, and the final approach leg. Testing on each profile was complete at the end of the final approach leg, which terminated at 200 feet above field elevation.

Phase IA examined these "typical" MLS approach profiles to determine which profiles and instrument systems were easier to fly and to ascertain the causes and effects of poor tracking performance.

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A

Initial
Leg

Turn 1

Crossleg

450°

Turn 2
Final
Approach
Leg

2NM.

Pattern
1
2NM./45°

B

Initial
Leg

Turn 1

Crossleg

60°

Turn 2
Final
Approach
Leg

2NM.

Pattern
2
2NM./60°

C

Initial
Leg

Turn 1

Crossleg

45°

Turn 2

Final
Approach
Leg

4NM.

Pattern
3
4NM./45°

D

Initial
Leg

Turn 1

60°

Crossleg

Turn 2

Final
Approach
Leg

4NM.

Pattern
4
4NM./60°

Figure 3.- Approach Patterns

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SECTION II

STUDY PROCEDURE

I. APPARATUS

This experiment was conducted in the Crew Station Design Facility, which has the capability to dynamically simulate a complete flight regime under a variety of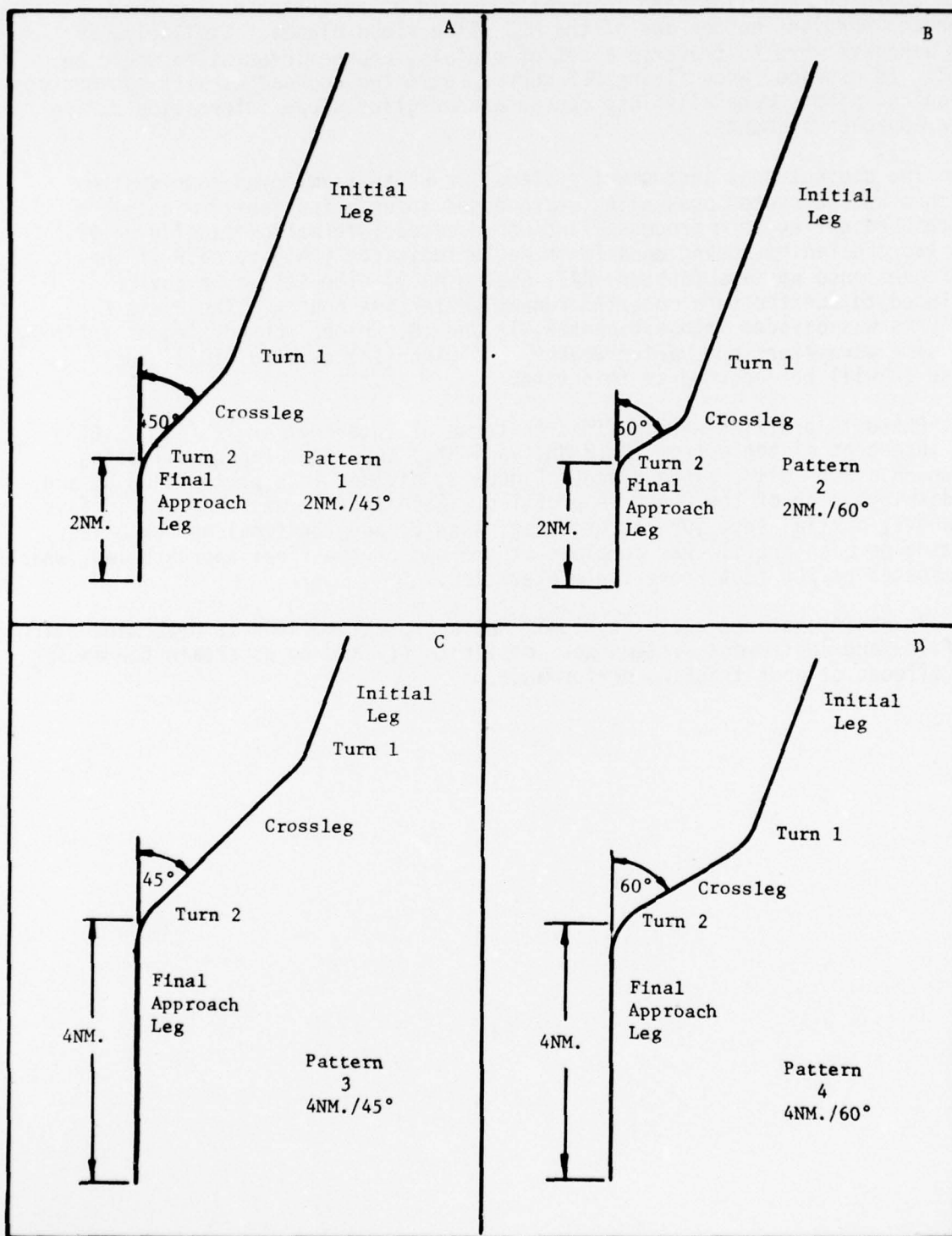 controlled conditions. For this study, the T-40 simulator was used. The T-40 crew station shell was mounted on a motion platform and could be moved in three dimensions: pitch, 15 degrees down and 25 degrees up; roll, 9 degrees depending on pitch angle; and $\pm$ 12 inches of vertical displacement. The Mark I digital computer controlled all the simulator's functions. With the magnetic tape unit, up to 64 separate parameters could be recorded at every 0.2 second. The parameters for this study are in appendix A. The visual simulation equipment was not used.

The crew station was configured as the T-39 test aircraft, including T-39 aerodynamics and instruments (Figure 4). The system contained an Attitude Director Indicator (ADI) powered by a CPU-4 Flight Director Computer. The pitch and bank steering bars operated as command information. Unprocessed glide slope deviation was displayed by a pointer moving beside a vertical scale that was located on the left side of the instrument face. On the bottom of the indicator were located a rate of turn indicator and an inclinometer. Unprocessed localizer deviation was displayed on the Course Deviation Indicator (CDI) on the Horizontal Situation Indicator (HSI). The HSI was located directly below the ADI. A heading set and a course set knob were on the left and right sides of the HSI, respectively. The knob rotated a small white heading indicator about the compass. The knob operated the digital course indicator in the upper right portion of the HSI and could reposition the CDI when the aircraft was receiving course information. The distance from the MLS azimuth transmitter was given by the three digit Distance Measuring Equipment (DME) readout in the upper left corner.

Mounted between the ADI and the HSI was the Azimuth Angle Indicator (AAI) (Figure 5). It displayed aircraft position (needle) in relation to a scale marked in degrees representing MLS radials. The 0° marker referred to the runway centerline extended radial and was located at the center of the scale. The scale extended out to 60° either side of the 0° mark in a nonlinear fashion with the larger units nearer the 0° mark. Aircraft position was displayed as though one were facing the runway and looking at the aircraft's horizontal position in relation to the MLS radials. The indication displayed in Figure 5 marks aircraft position as some point on the 20° left radial, which corresponds to the radial used for the Initial Leg of all Phase IA profiles.

Bank and pitch command bars and the AAI could be removed from sight via switches on the experimenter's panel. Through switching, the four instrument configurations described in the introduction were created. An austere system

1. Angle of Attack Indicator
2. Airspeed Indicator
3. Radar Altimeter
4. Attitude Director Indicator
5. Azimuth Angle Indicator
6. Horizontal Situation Indicator
7. Clock
8. Vertical Velocity Indicator
9. Barometric Altimeter
10. Azimuth Angle Selector
11. Glide Slope Plane Selector
12. Exhaust Pressure
13. Tachometer
14. Exhaust Gas
15. Fuel Flow
16. Oil Pressure
17. Fuel Quantity

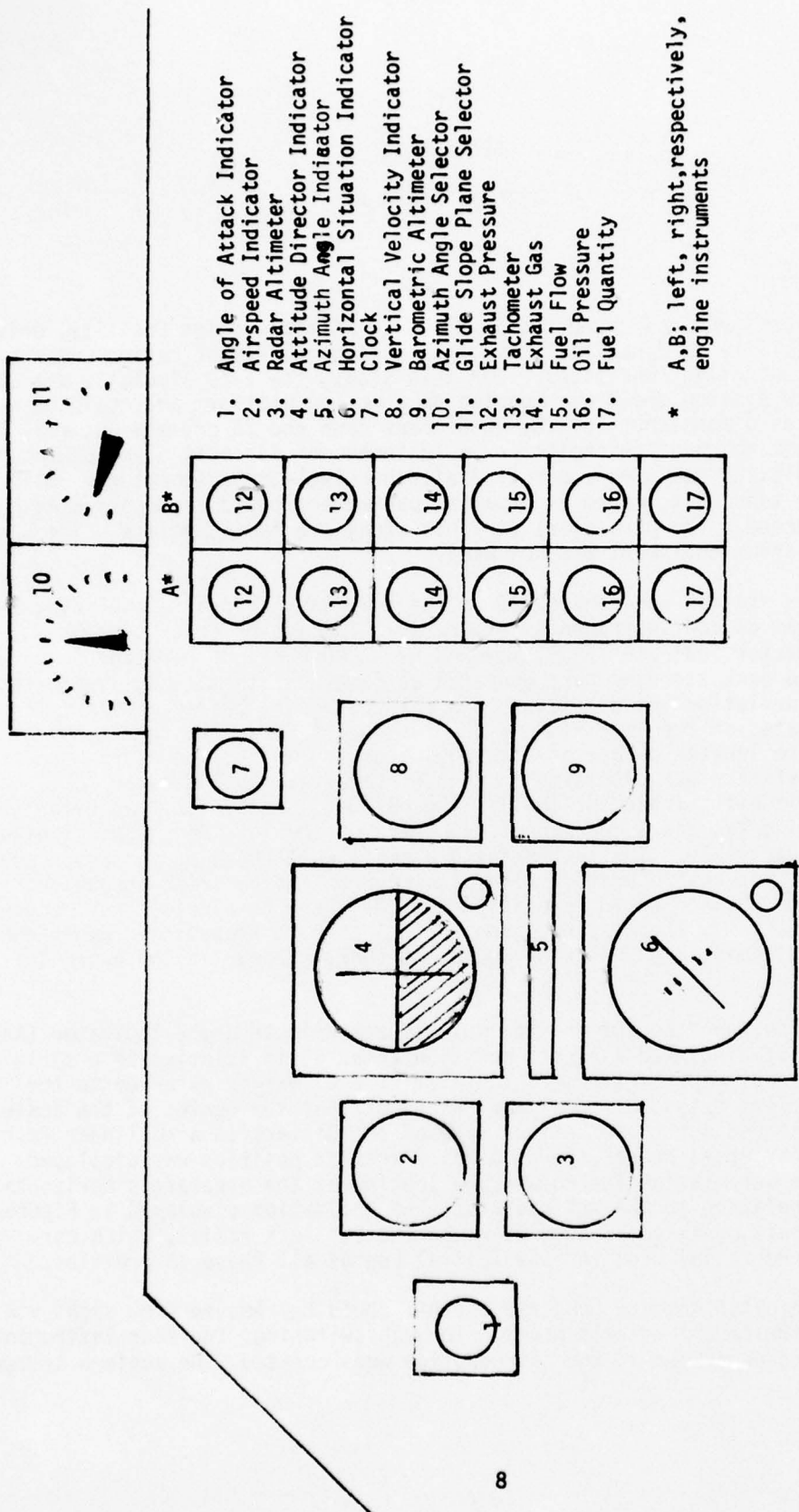* A,B; left, right, respectively, engine instruments

Figure 4.

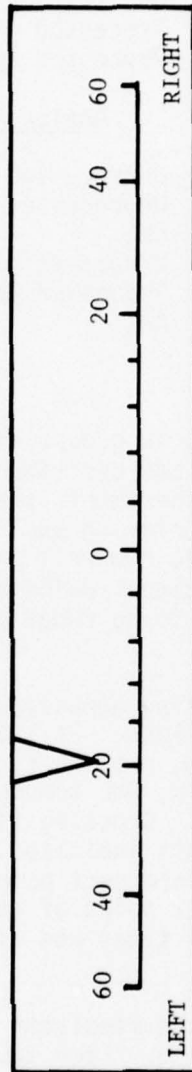Instrument Configuration

AAI

Figure 5.- Azimuth Angle Indicator

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was an analog system minus command bars. An AAI system was simply either an austere or analog system with an operating AIAA. All are described below:

Austere

1. Unprocessed glide slope
2. Unprocessed localizer
3. DME

Analog

1. Unprocessed glide slope
2. Unprocessed localizer
3. DME
4. Processed glide slope
5. Processed localizer

Austere AAI

1. Unprocessed glide slope
2. Unprocessed localizer
3. DME
4. AAI

Analog AAI

1. Unprocessed glide slope
2. Unprocessed localizer
3. DME
4. Processed glide slope
5. Processed localizer
6. AAI

2. PROCEDURE

The pilots served in the experiment in groups of three. The experimenter briefed each group during ground school and described the physical characteristics of the MLS, the purpose of the experiment, the experimental design, and additional pilot procedural data. The briefing explained to the pilots that the purpose of the experiment was to evaluate how well pilots could fly the MLS approach profiles selected using conventional avionics. Each was explicitly told that his performance was not going to be compared with that of other pilots.

The procedures portion of the briefing emphasized the need for a "best professional effort" from the subject pilots. It included a presentation on MLS geometry, instrument system and location, pattern type (all planar), heading and course settings required for each pattern, DME turnpoints per pattern, and crossleg distances and time per pattern. Crossleg times were the estimated time of travel based on a constant 140 kts indicated air speed (IAS) and the crossleg distance as measured from the intersect point of the crossleg and the 20° radial (initial leg) to the intersect point of the crossleg and the 0° radial (final approach leg). The actual times and distances are shown in Appendix B.

The briefing ended with a trip to the simulator to acquaint pilots with the testing situation and to begin testing. Each subject began flying with ten practice approaches in groups of five each for familiarization and training.

The procedures at the beginning of each test approach were the same for all twelve subjects. The simulator was automatically positioned and held at the start point (12 NM. DME, 20° radial) and near the proper altitude. The experimenter then gave to the pilot via console switches the instrument

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configuration to be used for the next four trials and the pattern number of the next approach to be flown. All analog approaches were flown in the ILS approach mode. The pilot then set in the appropriate crossleg heading on the HSI, the correct inbound course (191° for all approaches) and dialed in the appropriate MLS radial on the MLS selector panel (20°L). When he had established the appropriate aircraft heading (191°) and airspeed (140 kts IAS), positioned the landing gear, speed brakes, and flaps to their fully down positions, he then asked to be released. The experiemnter pushed the appropriate console button and the simulator departed from the start point under the pilot's control.

The pilot flew the initial leg and initiated turn 1 based on the DME readout. Since none of the configurations could present course guidance or turn 1, the pilot was required to note DME as he was tracking the initial leg (20° radial) and initiate turn 1 when the appropriate DME for that pattern was reached. However, the DME readout was in integers (e.g., 7.0) whereas the DME turnpoints were in tenths (e.g., 7.4). After the completion of turn 1, pilots rolled out on the crossleg heading, increased the throttle setting to maintain glide slope, and flew heading only, since no crossleg course guidance was available.

At some point of his choosing during turn 1, the pilot could have started the timer to cue turn 2. During some portion of the crossleg the azimuth selector switch must be changed from 20°L to 0° and the HSI course setting must be changed from 191° to 171°. If both were not done the airborne receiver would not capture the runway heading localizer beam (LOC). At some time during the crossleg the pilot, at his discretion, initiated a left bank for turn 2. Since no course information was presented, three alternative cueing methods were devised. The pilot could initiate turn 2 based on elapsed time (i.e., time from turn 1), AAI (if present), or CDI deflection. After entering turn 2, the pilot would then decrease engine power and attempt to roll out the 0° radial (final approach leg) and on glide slope.

After the aircraft flew below 200 feet above ground altitude, that approach was terminated and the aircraft was repositioned for another approach. Each pilot flew four consecutive approaches before a different pilot began testing. After each four approach set every pilot answered a post mission questionnaire (Appendix C). Each pilot flew a total of 32 test approaches, after which he then answered an MLS end of study questionnaire.

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3. SUBJECTS

The subjects were 12 USAF pilots. Three pilots each were obtained from ADC, SAC, MAC, and IFC.

SUBJECT	AERO RATING	COMMAND	TOTAL FLYING HOURS
1	Sr Pilot	SAC	2,700
2	Pilot	SAC	2,600
3	Pilot	SAC	1,800
4	Sr Pilot	ADC	3,200
5	Pilot	ADC	1,300
6	Pilot	ADC	500
7	Pilot	MAC	3,200
8	Pilot	MAC	2,900
9	Pilot	MAC	1,900
10	Sr Pilot	IFC	2,500
11	Sr Pilot	IFC	4,500
12	Sr Pilot	IFC	5,600

AVERAGE 2,725

4. EXPERIMENTAL DESIGN

Four factors were used as independent variables. They were: instrument configuration, localizer beam width, intercept angle and intercept distance. A $2.5°$ glide slope angle was used throughout. The levels were as follows:

Factors	Levels
Instrument configuration	Austere, Analog, Austere AAI, Analog AAI
Localizer beam width	$+ 2.5°$, $+ 5.0°$
Intercept angle	$45°$, $60°$
Intercept distance (from TD)	2 NM., 4 NM.

Each pilot flew ten practice trials (in groups of five each) to familiarize himself with the simulator. The four factors and their combinations resulted in 32 different test conditions. In this study the test conditions were grouped in four approach sessions (i.e., mission). Each mission had only one instrument configuration and localizer beam width. In each mission all possible combinations of intercept distance and intercept angle were given. Each pilot flew two missions on each day of the four day test period. Each pilot flew 32 test approaches in all and received each of the 32 different test conditions once. During the experiment, the test conditions were reordered from subject to subject to control for practice effects. In total, 384 test approaches were flown. A breakdown of the data collected is presented in Tables 1 and 2.

The dependent variables in this study were primarily tracking error, and airspeed error. Tracking error scores included a lateral error score (Y), a vertical error score (Z) and a combination score (YZ). All three scores indicate how closely the pilot flew the aircraft to the nominal track. Airspeed error measured how closely the pilot maintained a constant 140 kts IAS throughout each approach. The scoring system is more thoroughly discussed in Subsection II-5.

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TABLE 1
NORMATIVE DATA

1.   96 Landings per Instrument Configuration
2. 192 Landings per Localizer Width
3. 192 Landigns per Intercept Distance
4. 192 Landings per Intercept Angle

TABLE 2
INTERACTION DATA

1. Equipment X Localizer		48 Landings/Condition
2. Equipment X Intercept Distance		48 Landings/Condition
3. Equipment X Intercept Angle		48 Landings/Condition
4. Equipment X Localizer X Intercept Distance		24 Landings/Condition
5. Equipment X Localizer X Intercept Angle		24 Landings/Condition
6. Equipment X Intercept Distance X Intercept Angle		24 Landings/Condition
7. Equipment X Localzier X Intercept Distance X Intercept Angle		12 Landings/Condition

5. SCORING SYSTEM

Each MLS pattern was divided into five legs for scoring (Figure 3). Leg 1 was the initial leg, which ended at the beginning of the first turn, leg 2. Leg 3, the crossleg, began at the end of the first turn and lead to leg 4, the second turn followed by leg 5, the final approach leg. The final approach ended when the aircraft was below 200 feet above ground altitude.

Within each leg, four parameters were tabulated to describe the aircraft's performance. Airspeed error score (A/S), lateral tracking error score (Y), vertical tracking error score (Z), and a combination score (YZ) consisting of both lateral and vertical tracking error, were collected. Each Y and Z value represents the actual distance in feet between the aircraft and the nominal track, laterally and vertically, respectively. Each YZ value was the distance in feet between the aircraft and the desired track and was calculated using the Y and Z value at each iteration and the Pythagorean Theorem. Each airspeed value was the difference between the aircraft indicated airspeed and 140 kts at each iteration. Each A/S, Y, Z, and YZ value were computed every 0.2 second, an absolute value determined, summed with the other values of that parameter for that leg, and divided by the number of iterations during that leg to produce a score for that parameter on that leg. Each parameter value and score (absolute average error term) were calculated depending upon leg number and pattern number.

Essentially, the scoring system tabulated a set of absolute average error (AAE) terms which described how closely the pilot flew the aircraft to the nominal track at the desired airspeed for each leg. Each AAE term reflects not only consistently poor performance but also tracking performance which oscillates about the nominal track. Differences among AAE terms for a particular parameter accurately reflect differences in tracking performance. The AAE terms, by their nature, are normalized for time and distance and therefore permit comparisons across pattern types.

Additional information is presented in Appendix D.

SECTION III

RESULTS AND DISCUSSION

An analysis of variance done on the combination scores for the initial leg (Table 3) showed only the instrument factor to be significant ($p \leq 0.05$)*. Reliable performance differences occurred between the scores for analog and austere instrument systems. This is graphically displayed by Figure 6, which shows performance as a function of pattern type and instrument configuration (analog/austere). As Figure 6 shows analog (processed information) mean error scores across patterns were consistently lower for all patterns than those for the austere (unprocessed information) systems. Essentially, significant initial leg performance differences were a function of processed/unprocessed information.

Analysis of the standard deviation scores shows that the standard deviation for the analog AAI condition (98.70) was statistically larger ($p \leq 0.05$) than the standard deviation for the analog only condition (76.9). The significantly larger standard deviation for the analog AAI indicates that performance was more erratic and suggests that the AAI had some disruptive effect upon performance when flying analog configurations. The AAI presentation conflicted with that of the CDI and the bank steering bar. For example, when the aircraft is left of the desired course, the AAI needle is left of the degree marking for that course, while the bank steering bar and the CDI needle are to the right of the course marker. The appropriate response to all of the indications is to bank right. It is plausible to suspect that such a situation, where opposite indications mean the same thing, would have a negative affect upon performance. However, since on any particular pattern the analog AAI mean error score is lower than either the austere only or the austere AAI mean, the influence on performance of the AAI/non-AAI factor is not as pronounced nor consistent as is that of the processed/unprocessed information factor.

A breakdown of the combination scores (Figure 7) into their Y and Z components, lateral and vertical tracking error respectively, reveals that the use of analog systems reduced both lateral and vertical tracking errors more than did the use of either austere system. However, the trend is much more pronounced for the lateral error (Y) scores, than for vertical error (Z) scores and shows that lateral course tracking difficulties contributed more to the YZ trend. Similar results were found for both the crossleg and final leg.

Airspeed error scores displayed in Table 4 show A/S error to be low and relatively constant across conditions on the initial leg. A/S error did not vary appreciably on the crossleg nor on the final approach leg. Apparently, pilots could control airspeed equally well under all conditions.

The results of an analysis of variance on the combination scores for crossing performances is shown in Table 5. The following factors were significant: intercept angle ($p \leq 0.01$), and the interaction of intercept

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*A p value represents how reliable the differences were. A value of 0.05 means that if the present study were run 100 times, for example, one would expect to find these same differences 95 times.

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TABLE 3

ANALYSIS OF VARIANCE SUMMARY
COMBINATION SCORES
INITIAL LEG

Factor	Sums of Squares (SS)	Degrees of Freedom (D.F.)	Mean Square (MS)	F Ratio (F)
Patterns (A)	27,894.0	3	9,298.00	.83
Instruments (b)	139,921.1	3	46,640.40	*4.66
Subjects (S)	181,848.7	11	16,531.70	
AB	84,399.6	9	9,377.73	
AS	371,635.8	33	11,261.70	
BS	330,624.0	33	10,018.90	
ABS	27,092,100.3	99	273,657.50	

* $p \leq 0.05$

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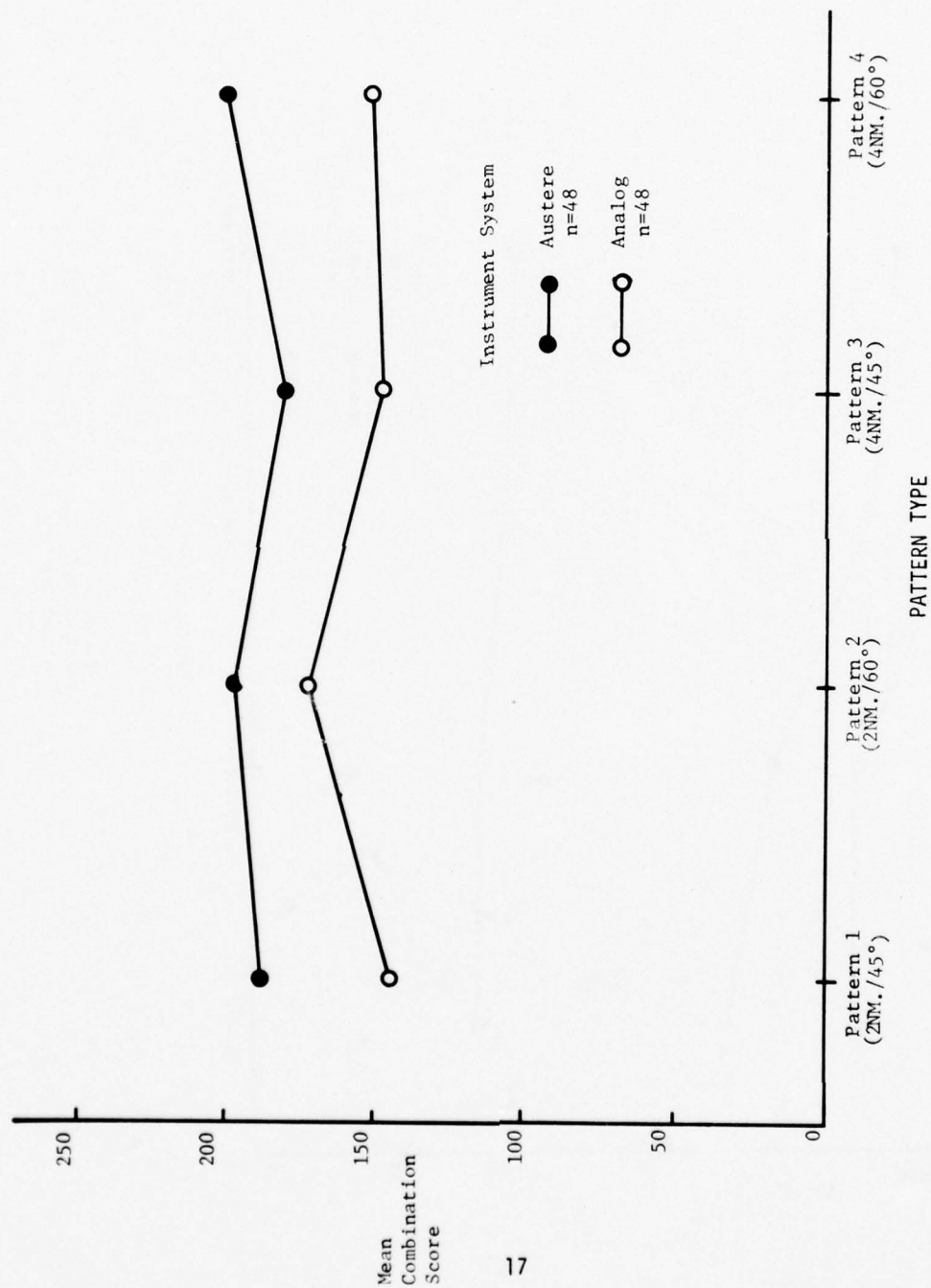
Figure 6
Initial Leg Performance

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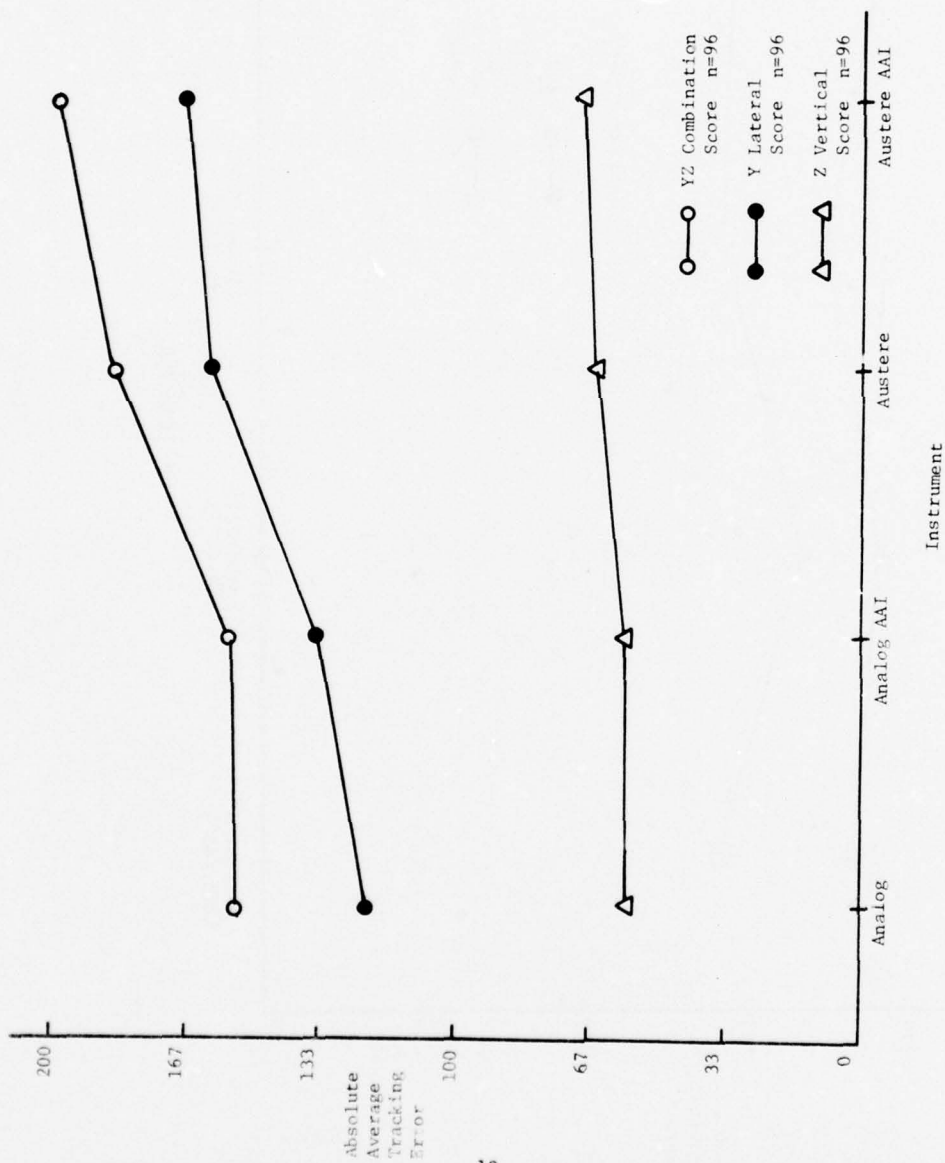
Figure 7
YZ-Y-Z Scores
Initial Leg

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TABLE 4

AIRSPEED AAE SCORES
INITIAL LEG

		Pattern 1 (2 NM./45°)	Pattern 2 (2 NM./60°	Pattern 3 (4 NM./45°)	Pattern 4 (4 NM./60°)	Total
Austere	mean	2.8	2.8	2.7	2.6	2.7
	S.D.	1.2	1.2	1.3	1.2	1.2
Analog	mean	3.1	3.4	3.0	3.3	3.2
	S.D.	1.3	1.8	1.0	1.9	1.5
Austere AAI	mean	2.5	2.8	2.9	3.3	2.9
	S.D.	1.3	1.2	1.1	1.9	1.4
Analog AAI	mean	3.3	2.5	3.3	3.2	3.1
	S.D.	1.6	.9	1.5	1.7	1.4
Total	mean	2.9	2.9	2.9	3.1	3.0
	S.D.	1.4	1.3	1.2	1.7	1.4

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TABLE 5

ANALYSIS OF VARIANCE SUMMARY
COMBINATION SCORES
CROSSLEG

Factor	Sums of Squares (SS)	Degrees of Freedom (D.F.)	Mean Square (MS)	F Ratio (F)
Instrument (A) (Analog/Austere)	1,012,228.0	1	1,012,208.0	3.07
Intercept Angle (B) (45°/60°)	6,280,051.1	1	6,280,051.1	*27.94
Intercept Distance (C) 2/4	1,848,559.0	1	1,848,559.0	4.66
AB Inst X Angle	152,581.0	1	152,581.0	0.32
AC Inst X Dist	55,203.6	1	55,203.6	0.22
BC Angle X Dist	5,918.0	1	5,918.0	0.02
ABC	366,138.8	1	366,138.8	*15.01
S Subj	6,813,652.0	11	619,423.0	
AS	3,631,317.0	11	330,119.7	
BS	2,472,841.0	11	224,803.8	
CS	4,361,592.0	11	396,508.4	
ABS	5,235,728.8	11	475,975.4	
ACS	2,781,438.6	11	252,858.1	
BCS	2,803,130.7	11	254,830.1	
ABCS	268,355.1	11	24,395.9	

*$p \leq 0.01$

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angle, intercept distance, and instrument ($p \leq 0.01$). The effect of intercept angle is apparent in Figure 8, a graph of crossleg performance as a function of mean combination scores. The error means peak on patterns 2 and 4, the 60° intercept angle approaches, and reflect that crossleg performance was poorer when flying 60° intercept angle approaches. Since there was no course information on the crossleg, if a pilot established the proper crossleg heading, then he would fly parallel to or track accurately the crossleg as a function of where he rolled out of turn 1.

All the turns in every profile were based upon a 4500 foot radius and could be flown accurately given that the pilot lead the turn accurately, maintained the proper airspeed and bank angle, and remained on the glide slope. Since turn 1, as well as turn 2, was flown without course guidance, no means were made available to correct course errors caused by slight errors in leading the turn, bank angle, or airspeed. Since turn 1 of 60° intercept approaches required a greater heading change than did turn 1 of a 45° intercept approach, one would expect pilots to be more off course at the turn 1 crossleg border on 60° intercept profiles. Given that no course information was available during the crossleg to correct course errors inherited from turn 1, such errors were perpetuated.

Even if the pilot maintained the proper airspeed and bank angle to inscribe a 4500 foot radius turn, an error in leading turn 1 could result in course error at the turn 1/crossleg border as follows: given equal turn 1 lead errors, the turn with the greater heading change would create more course error at the turn 1/crossleg border. Thus, there are reasons why higher intercept angle approaches could have caused pilots to be more off course at the end of turn 1 and thereby have had more crossleg tracking error. However, as the significant interaction term shows, crossleg performance differences were influenced by factors other than intercept angle.

Figure 8 shows that the difference between analog and austere means on patterns 1, 2, and 3 are essentially the same (approximately 70 units). Pattern 4 reveals a different situation. Here the difference between analog and austere means is 230 units (significant at $p \leq 0.05$). These differences show that the inclusion of processed information (analog) reduced tracking error on the most difficult crossleg, pattern 4.

Figure 9 depicts the three factor interaction of intercept angle, intercept distance, and instrument systems in a different format. The relative ranking of the four intercept distance/instrument configuration terms changed from the 45° to the 60° levels. When going to the 60° level from the 45° level, all the intercept distance/instrument configuration means increased markedly, except for the analog/4 NM. mean, which does not increase nearly as much. In essence, although the 60° intercept approaches were harder to fly, they were apparently made easier by the inclusion of processed information on 4 NM. approaches.

Figure 8
Crossleg Performance

Mean
Combination
Score

PATTERN TYPE

Pattern 1
(2NM./45°)

Pattern 2
(2NM./60°)

Pattern 3
(4NM./45°)

Pattern 4
(4NM./60°)

Analog   n=48
Austere   n=48

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Intercept Distance/Inst.

Austere/2NM.　n=48

Austere/4NM.　n=48

Analog /2NM.　n=48

Analog /4NM.　n=48

1000

900

800

700

600

500

400

Mean
Combination
Score

45°

60°

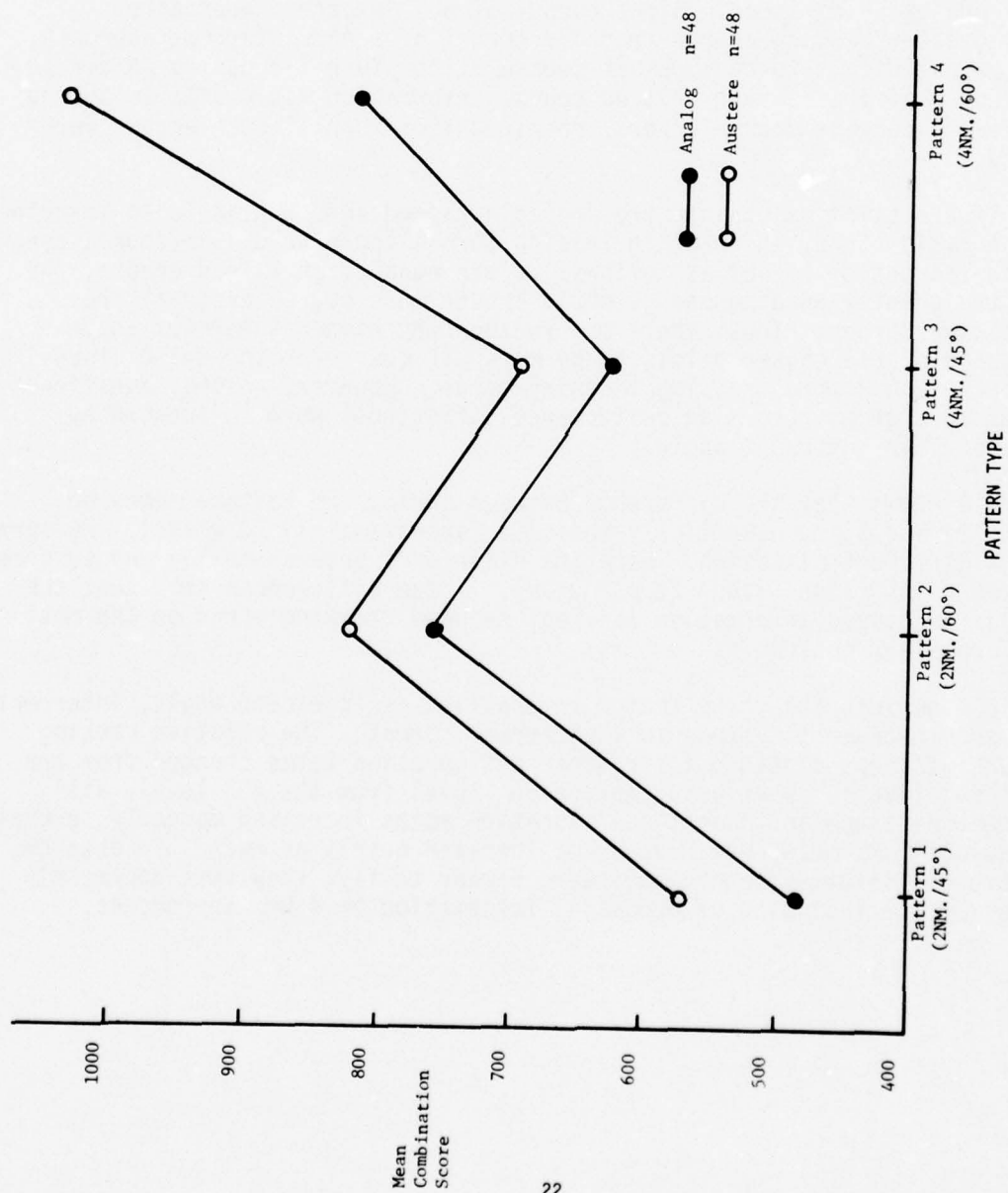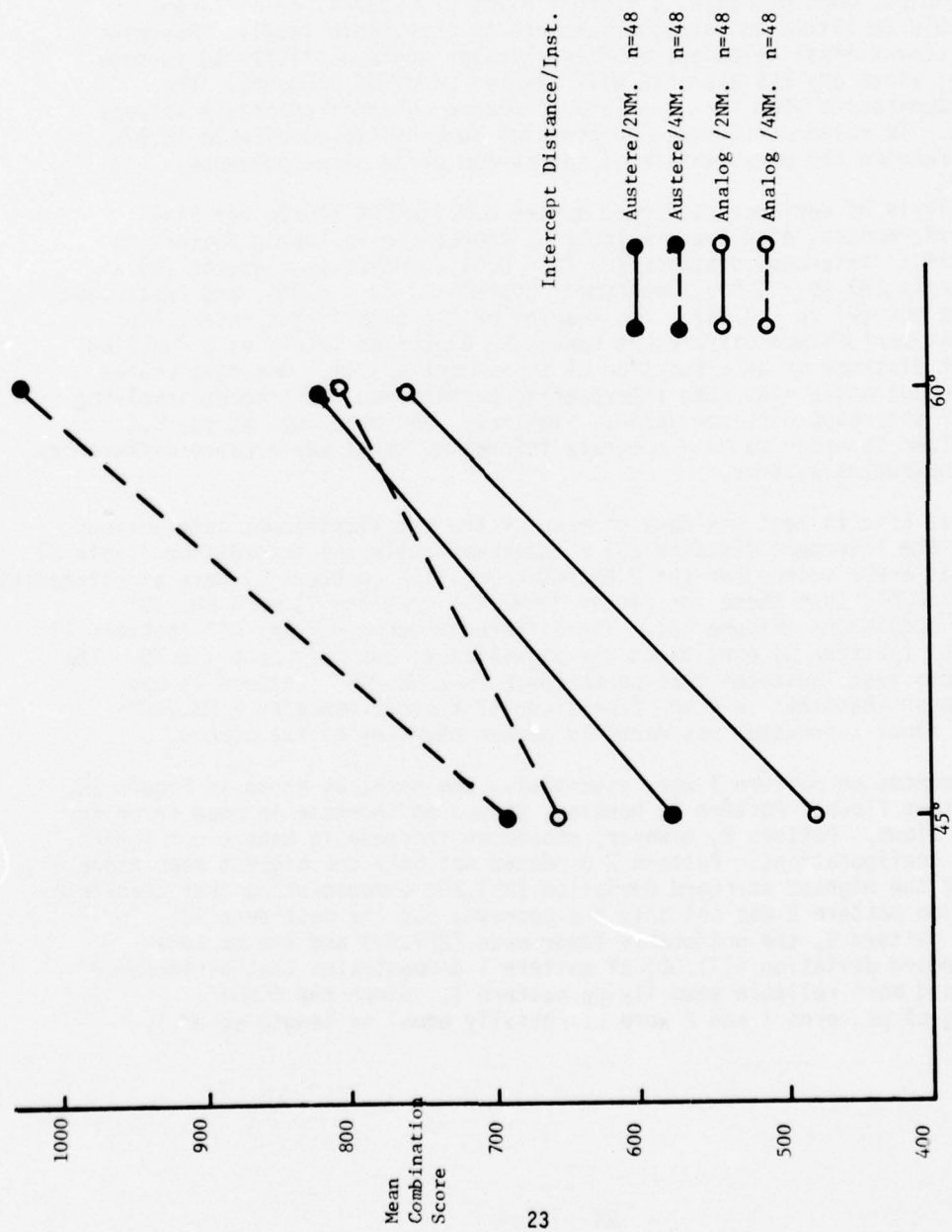Intercept Angle

Figure 9
Intercept Angle vs.
Intercept Distance/Instrument

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Although the experimental factors did produce significant relative performance differences, a basic problem still remains. Even the significantly better performances were, in an objective sense, poor. Examination of the standard deviations for instrument system/pattern type conditions on the crossleg shows that in each condition the standard deviation almost equals the mean. This indicates that the dispersion of scores is large and that each condition contains many very high error scores. The simultaneous occurrence of very high means and high standard deviation scores shows that performance was both poor and erratic: hence unacceptable. Given the present avionics, more practice, different pilot procedures, or different training would do little to raise performance to acceptable levels. Assuming the use of conventional avionics, profile redesign would do little to improve performance, since any MLS approach will involve unguided segments. The present circumstances show that the loss of course guidance adversely affects performance. To raise performance on crossleg segments to acceptable levels would thus require the presentation of course and glide slope guidance.

An analysis of variance performed on the combination scores for Final Approach performances, displayed in Table 6, showed the following factors to be significant: intercept distance (C) ($p \leq 0.01$), intercept distance (C) x intercept angle (B) ($p \leq 0.05$), instrument system (A) ($p \leq 0.05$), and instrument system (A) x LOC (D) ($p \leq 0.01$). The meaning of the significant interaction terms is that performance differences cannot be explained solely as a function of intercept distance or as a function of instrument system. One must relate to the intercept angle used when interpreting performance differences involving a particular intercept distance value. Similarly, one must look at the LOC condition flown in order to make accurate inferences about performance differences involving instrument systems.

A Simple Effects test was done on each of the two significant interactions. The test on the intercept distance (C) x intercept angle (B) interaction (Table 7) revealed that error scores for the 2 NM./60° condition (pattern 2) were significantly greater ($p \leq 0.01$) that those for either 2 NM./45° (pattern 1) or 4 NM./60° (pattern 4) conditions (Figure 10). The difference between 2 NM./45° (pattern 1) and 4 NM./45° (pattern 3) conditions was significant, but only at $p \leq 0.10$. The Simple Effects test indicates that performance on 2 NM./45° (pattern 1) was somewhat poorer than that on 4 NM. finals and that performance on 2 NM./60° (pattern 2) final approaches was markedly poorer than any of the others.

Performances on pattern 1 were essentially the same, as shown in Figure 10, for all systems flown. Pattern 2, however, showed an increase in mean error for all systems flown. Pattern 2, however, showed an increase in mean error scores for non-AAI configurations. Pattern 2 produced not only the highest mean score (292.63) but the highest standard deviation (261.30) demonstrating that tracking performance on pattern 2 was not only the poorest, but the most erratic. In contrast to pattern 2, the noticeably lower mean (227.90) and the markedly reduced standard deviation (171.00) of pattern 1 demonstrates that performance was better and more reliable when flying pattern 1. Since the final approach leg of patterns 1 and 2 were essentially equal in length (2 NM.),

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TABLE 6

ANALYSIS OF VARIANCE SUMMARY
COMBINATION SCORES
FINAL LEG

Factor	Sums of Squares (SS)	Degrees of Freedom (D.F.)	Mean Square (MS)	F Ratio (F)
*A Inst	280,937.0	3	93,645.0	*3.06
B Intercept Angle (45°/60°)	41,861.0	1	41,861.0	2.37
*C Intercept Distance (2 NM./4 NM.)	1,136,570.0	1	1,136,570.0	*26.28
D LOC (2.5°/5.0°)	44,081.0	1	44,081.0	0.58
AB Inst X Angle	154,818.0	3	51,394.0	1.97
AC Inst X Dist	11,847.0	3	3,949.0	0.15
*AD Inst X LOC	438,247.0	3	146,082.0	*6.23
*BC Angle X Dist	183,419.0	1	183,419.0	*6.26
BD Angle X LOC	58,603.0	1	58,603.0	2.00
CD Dist X LOC	1,580.0	1	1,580.0	0.04
ABC Inst X Angle X Dist	123,303.0	3	41,101.0	1.60
ABD Inst X Angle X LOC	24,887.0	3	8,295.0	0.27
ACD Inst X Dist X LOC	109,613.0	3	36,537.0	2.63
BCD Angle X Dist X LOC	24,908.0	1	24,908.0	1.79
ABCD Inst X Angle X Dist X LOC	33,424.0	3	11,141.0	

TABLE 6 (CONTINUED)

ANOVA

Error Term	Sums of Squares (SS)	Degrees of Freedom (D.F.)	Mean Square (MS)
AS	1,010,725	33	30,628
BS	194,574	11	17,688
CS	475,664	11	43,242
DS	831,427	11	75,584
ABS	860,508	33	26,076
ACS	845,956	33	25,635
ADS	774,222	33	23,461
BCS	322,447	11	29,313
BDS	322,240	11	29,240
CDS	495,807	11	45,073
ABCS	846,705	33	25,657
ABDS	1,005,589	33	30,472
ACDS	458,288	33	13,887
BCDS	458,289	11	13,887
ABCDS	1,708,941	33	51,786

TABLE 7

SIMPLE EFFECTS TEST
INTERCEPT DISTANCE/INTERCEPT ANGLE
INTERACTION

Source	Sums of Squares (SS)	Degrees of Freedom (D.F.)	Mean Square (MS)	F Ratio (F)
Angle @ 2 NM.	200,932.9	1	200,932.9	**11.36
Angle @ 4 NM.	24,733.9	1	24,733.9	1.40
Distance @ 45°	203,424.4	1	203,424.4	*4.70
Distance @ 60°	1,116,300.0	1	1,116,300.0	***25.82
Angle X S	17,688.0	1	17,688.0	
Distance X S	43,242.0	1	43,242.0	

* $p \leq 0.10$
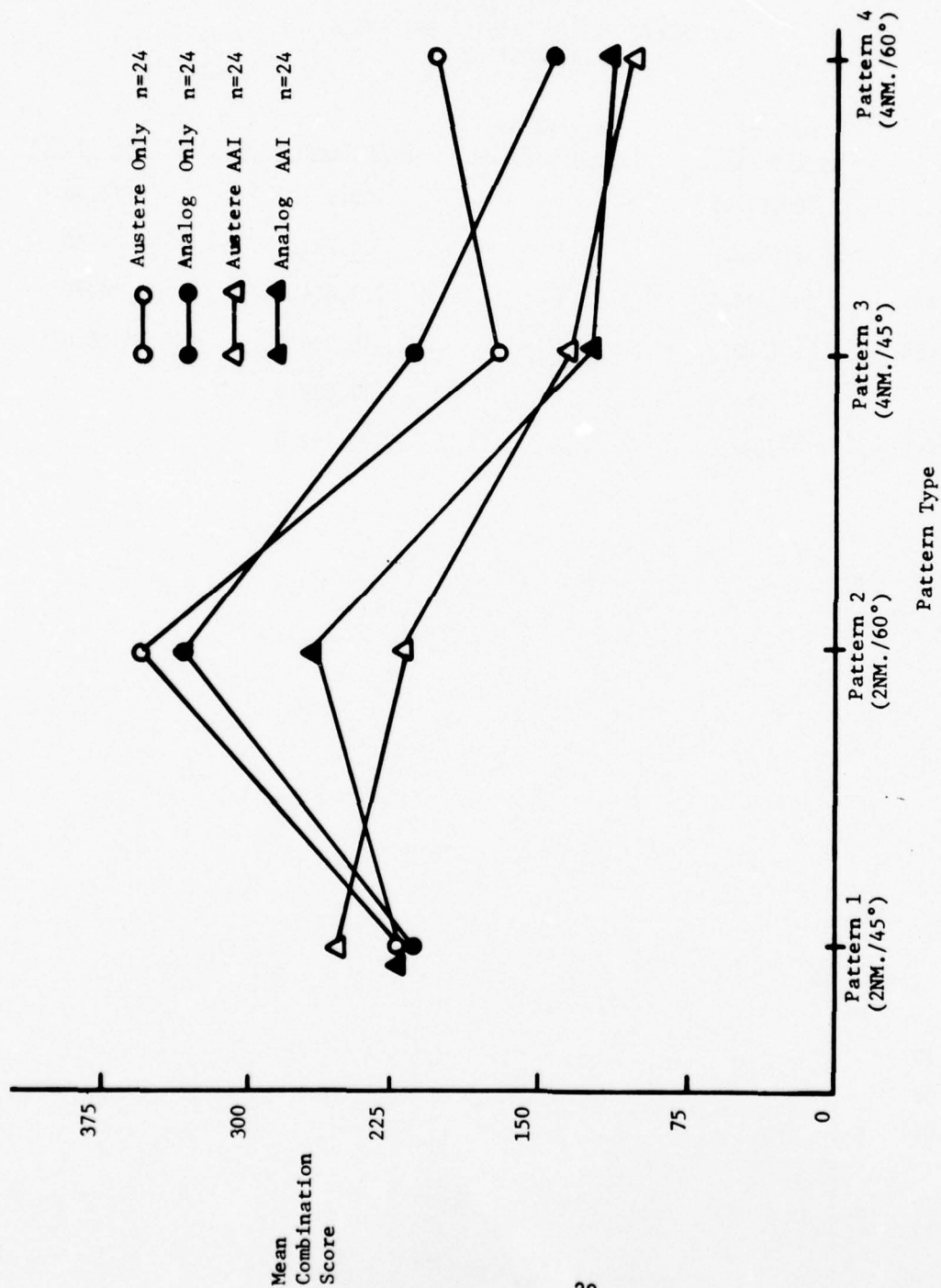** $p \leq 0.05$
*** $p \leq 0.01$

Figure 10
Final Leg Performance

they offered equal time to correct tracking errors inherited from turn 2. Thus, the noteworthy performance differences between patterns 1 and 2 indicate that there were more difficulties in capturing the final approach beam of pattern 2. This was caused by excessively poor performance in turn 2 of pattern 2.

Patterns 1 and 2 have higher means (227.9 and 292.6, respectively) and standard deviations (171.0 and 261.3, respectively) that patterns 3 and 4, which have means of 162.8 and 140.1 and standard deviations of 103.8 and 88.50, respectively. Apparently final approach performance becomes somewhat better and more reliable on patterns 3 and 4, which have longer final approach legs.

Intercept angle appears to be the crucial factor in the profile design of patterns 1 and 2. The higher intercept angle of pattern 2 caused appreciably higher tracking error scores. The negative effect of the high intercept angle was not apparent on the final leg performance of patterns 3 and 4. They allowed more time to correct tracking errors occurring during turn 2 and thereby allowed any effect of intercept angle on turn 2 performance to be obscured. In essence, the effect of intercept angle was pronounced on profiles with intercept distances and ineffectual on profiles with 4 NM. finals.

The Simple Effects test on the instrument (A) x LOC (D) interaction (Table 8) showed that performance on the austere only/$\pm$ 2.5° LOC condition was significantly poorer ($p \leq 0.01$) than on the austere only $\pm$ 5.0° LOC condition. In addition, performance on the austere AAI/$\pm$ 2.5° LOC condition was significantly better ($p \leq 0.01$) than that on austere AAI/$\pm$ 5.0° LOC condition. Means on the $\pm$ 2.5° LOC factor across instrument conditions were found to differ significantly ($p \leq 0.05$). A Simple Effects test demonstrated that on the $\pm$ 2.5° LOC factor, performance on either austere or analog only systems was significantly poorer ($p \leq 0.05$) than on either AAI system.

Figure 11 is a graph relating localizer beam width and instrument systems to final leg performance. The means are significantly higher for the non-AAI/$\pm$ 2.5° LOC conditions than for non-AAI/$\pm$ 5.0° LOC conditions. This indicates that even though neither width LOC beam could have been used to cue turn 2 soon enough to have prevented overshoot, the broader beam gave an earlier cue and thereby reduced overshoot errors. Examination of the $\pm$ 5.0° condition shows no appreciable difference between AAI and non-AAI means and suggests that the AAI is no better than the broader LOC beam at reducing overshoot errors. However, AAI/$\pm$ 2.5° LOC condition means are significantly lower than non-AAI/$\pm$ 2.5° LOC condition which shows that performance improved on the $\pm$ 2.5 condition when the AAI was added.

The austere AAI/$\pm$ 2.5° LOC mean is significantly lower than the austere AAI/$\pm$ 5.0° LOC and shows that the narrower LOC beam, when capture problems had been alleviated, actually provided better tracking information. Tracking the narrower beam allowed the pilot to perceive smaller course errors and to stay closer to the desired course. When tracking the $\pm$ 2.5° LOC beam, CDI deflections for any off-course distance were twice the size of those obtained when tracking the $\pm$ 5.0° LOC beam for the same off course distance. In summary, the AAI improved final leg performance by reducing capture problems, but only when the narrower LOC beam was captured. Once accurately captured, the narrower beam fostered better tracking performance when tracking was done via unprocessed information.

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TABLE 8

SIMPLE EFFECTS TEST
INSTRUMENT/LOC INTERACTION

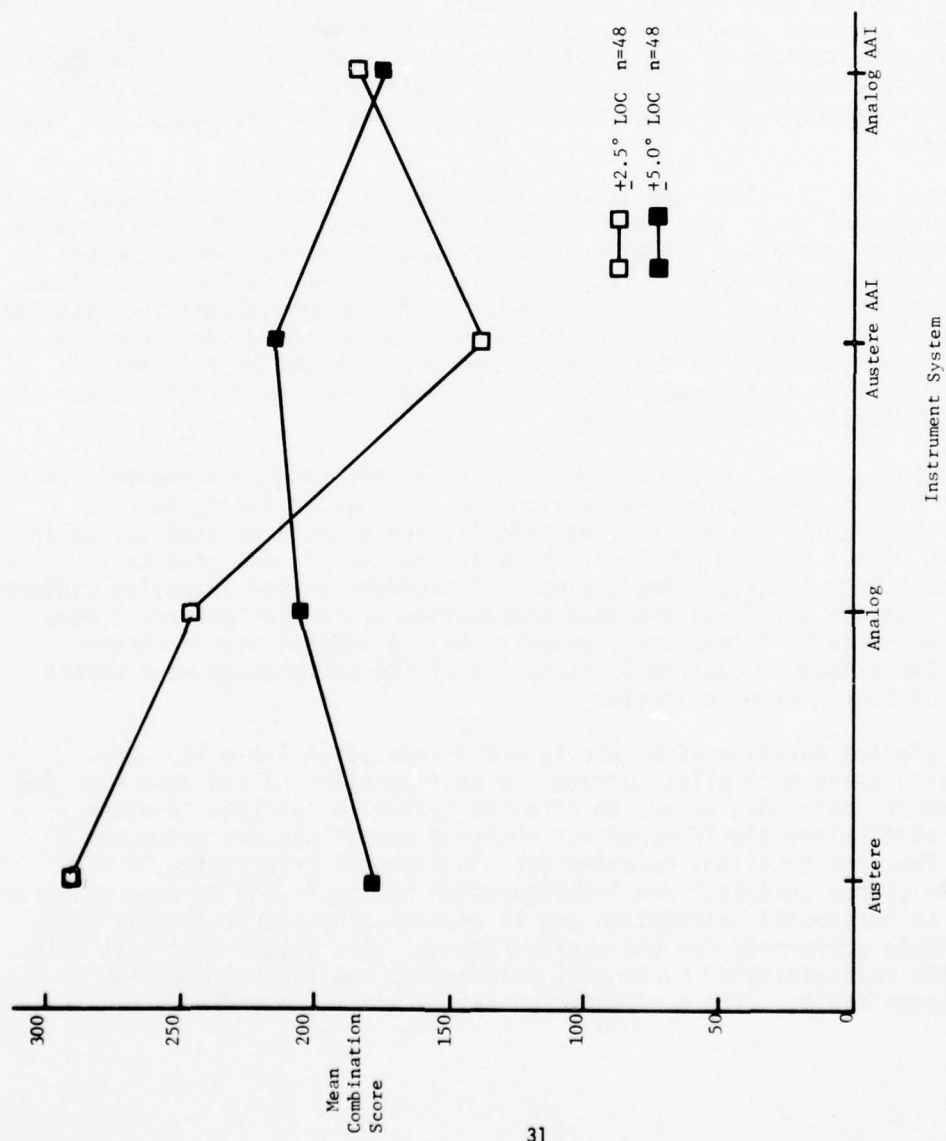| Source	Sums of Squares (SS)	Degrees of Freedom (D.F.)	Mean Square (MS)	F Ratio (F)
LOC @ Austere only	293,298.8	1	293,598.8	**10.86
LOC @ Analog only	40,713.8	1	40,713.8	1.51
LOC @ Austere AAI	150,258.0	1	150,258.0	* 5.56
LOC @ Analog AAI	3,876.1	1	3,876.1	0.14
Instrument @ $\pm2.5°$ LOC	662,955.4	3	220,985.1	* 6.06
Instrument @ $\pm5.0°$ LOC	63,530.3	3	21,176.8	0.58
LOC X S	842,468.5	33	27,044.5	
Instrument X S	401,401.0	11	36,491.8	

* $p \leq 0.05$
** ≤ 0.01

Figure 11
Instrument vs. LOC
Final Leg

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The effects of inaccurate capture are also apparent at the end of the final leg, as described by gate 5 scores, a set of scores taken as the aircraft passed through the 200 feet above ground point on the final leg. Figure 12, a graph of lateral error gate 5 scores, shows some pronounced trends. Error means for pattern 2 are appreciably higher than those for any other profile, just as they were for final approach performance scores. For analysis, a criteria of 100 feet off course in either lateral direction was applied to each gate 5 lateral score. Table 9a displays the scores labeled according to the above cited criteria. Only a slight effect of instrument configuration appears. However, pattern type has influenced performance as shown by the appreciable difference between the pattern 2 score (51%) and the others (28%-15%). A Friedman One Way Analysis of variance done on the instrument scores and on the pattern scores demonstrated that only pattern scores differed significantly. This would indicate that pattern 2 caused more aircraft to be beyond the 100 ft course error criteria than did any of the other patterns. Specifically, exceedingly poor capture of the final beam caused course error that frequently went uncorrected throughout the final leg of pattern 2. As a result during many of the approaches, the aircraft had deviated too far off course and remained so until gate 5.

The gate 5 glide slope scores were organized and labeled based upon whether or not a score indicated an error in excess of 25 feet low. The percent beyond criteria scores, presented in Table 9b, show that the dispersion of beyond criteria scores for the pattern factor and the instrument factor ranged from 6% to 22% and from 10% to 24%, respectively. The low percentages indicate that few of the aircraft passing through ate 5 were low on the glide slope. A Friedman One Way Analysis of Variance was performed on the beyond criteria scores across patterns and across instruments and illustrated that neither factor had a statistically significant effect.

In summary, capture problems dominated final approach performance. These problems were caused by the absence of course information during turn 2. Instrument configurations and LOC beam widths, which could be used to cue in turn 2, did reduce capture problems. However, pattern 2, designed to incorporate a high intercept angle close to touchdown caused extensive capture problems. Many of the final approach combination scores for pattern 2 were large and were caused by capture problems. Gate 5 lateral scores further emphasize the effect of pattern 2, since 51% of the performance were beyond the 100 foot course error criteria.

Post mission questionnaire results are presented in Table 10. The questionnaire asked each pilot to rate the configuration he had just flow and did not ask or imply that he was to rate the system in relation to other systems. Statictical significance was obtained across systems using the Cochran Q Test for questions relating to: "horizontal orientation," "anticipate course changes," and "configuration rating." The percent positive responses to horizontal orientation and to anticipating course changes show an appreciable preference for AAI configurations. The pilots felt that the AAI made the maintaining of horizontal orientation and the anticipating of course changes easier. The configuration rating scale (Appendix C) places a
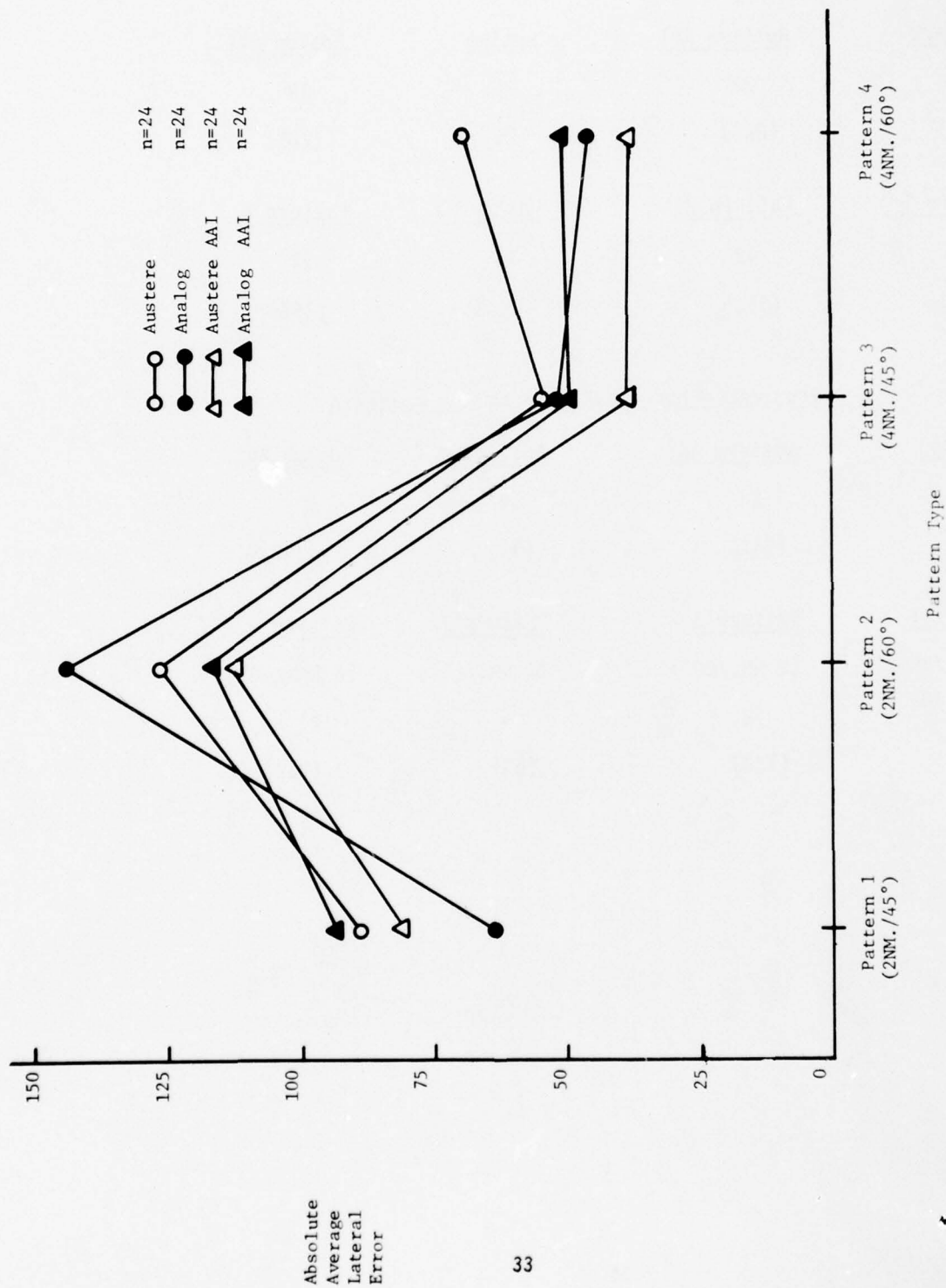
Figure 12

Gate 5 Lateral Performance

TABLE 9

a. LATERAL SCORES BEYOND ± 100 FT CRITERIA

Austere	Austere AAI	Analog	Analog AAI
38	25	25	19
(40%)	(26%)	(26%)	(20%)

Pattern 1	Pattern 2	Pattern 3	Pattern 4
27	49	14	14
(28%)	(51%)	(15%)	(15%)

b. VERTICAL SCORES BEYOND 25 FT LOW CRITERIA

Austere	Austere AAI	Analog	Analog AAI
13	23	9	10
(14%)	(24%)	(9%)	(10%)

Pattern 1	Pattern 2	Pattern 3	Pattern 4
(2 NM./45°)	(2 NM./60°)	(4 NM./45°)	(4 NM./60°)
15	12	6	21
(16%)	(13%)	(6%)	(22%)

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TABLE 10

POST-MISSION QUESTIONNAIRE RESULTS

	<u>AUS</u>	<u>ANA</u>	<u>AUS AAI</u>	<u>ANA AAI</u>
*Horizontal Orientation	36%	36%	82%	77%)
*Anticipate Course Changes	27%	23%	77%	82%
Maintaining Glide Slope	64%	59%	55%	55%
Tracking Throughout Approach	13%	36%	45%	36%
Configuration Rating	5.7	5.7	4.1	4.6

% - Positive Responses

* - Significant at $p \leq 0.05$

more positive (preferred) value on lower numerical ratings. The average ratings given for "configuration rating" are significantly lower for AAI configurations. However, none of the averages are any more favorable than "satisfactory." In general, pilots preferred the instrument systems containing more azimuth information, but felt none was exceptionally well suited for the given situation. This questionnaire data points to a desire by pilots for more azimuth information and highlights the need for avionics innovations to better cope with curved segmented approaches.

The End of Study Questionnaire responses are included in Appendix E. In general, the difficulty of flying MLS approaches with conventional avionics was discussed. Pilots consistently referred to an inability to accurately cue turn 2 and discussed how they attempted to cope with the problem.

SECTION IV

CONCLUSIONS

The difference in combination scores on the initial leg was a function of austere/analog systems. Analog systems significantly reduced tracking errors. The improvement indicates that processed information was beneficial because it not only includes off track error but error rate in creating the steering command. As a result, processed information, when properly followed, steers the aircraft back to the desired track with less probability of an overshoot. With the use of unprocessed information the pilot is required to estimate error rate and make his course and glide slope adjustments accordingly. More inaccuracies resulted.

The predominant problem is crossleg performance was not glide slope tracking, but accurate course tracking. This was expected and directly attributable to the lack of course guidance during turn 1 and the crossleg. Some significant performance differences due to intercept angle and an intercept angle/intercept distance/instrument interaction occurred. Poorer performance occurred on higher intercept angles, but the magnitude of the effect was dependnet upon the particular intercept distance/instrument system examined. Greater error on crosslegs intercepting at 60° was due predominantly to increases in lateral navigation problems caused by greater turn 1 heading changes made without course guidance. The meaning of the interaction term is that although the 60° intercepts were generally harder to fly, they were apparently made easier by the inclusion of processed information on 4 NM. approaches. However, none of the conditions on the crossleg fostered good performance, as defined by the range of tracking error scores obtained on the initial leg. All of the means and standard deviation statistics were much greater for crossleg conditions than for the corresponding conditions on the initial leg. The concurrence on the crossleg high error means and high standard deviations indicates that performance was unacceptable, which was due to the loss of course guidance during turn 1 and on the crossleg. Hence, to discuss which intercept angle, for example, caused more or less unacceptable performance may not be as pertinent as describing a means to change unacceptable to acceptable performance. Such a change would occur, if course guidance were given on turn 1 and on the crossleg.

Under present circumstances, pilots have to perform many tasks on the crossleg; for example, roll out of turn 1, throttle adjustments, change of azimuth selector, change of course set, cueing turn 2 via some means, and initiating a bank to make turn 2. Considering that the tasks are performed in serial, shorter crosslegs would increase task compression and make leading turn 2 more difficult. Since pattern 2 has the shortest crossleg, task compression combined with the 60° heading change fostered especially poor turn 2 performance. Notably on pattern 2, but on other profiles as well, there was the tendency for course error to dominate final approach tracking error scores. This was primarily caused by inaccurate capture of the final approach beam. By including a means (AAI or $\pm 5.0°$ LOC beam) to cue turn 2, capture problems were reduced. The test overall final approach performance was with the austere AAI/$\pm 2.5°$ LOC condition. Hence, once capture problems were

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reduced, tracking improved when following a more sensitive source of information, the $\pm$ 2.5° LOC beam. Yet, the demonstrably poorer performance found for pattern 2 on the final approach leg and at gate 5 indicate that large capture errors occurring at the 2 NM./60° intercept point were too great to be corrected by gate 5.

Many of the consequences of flying curved/segmented profiles are apparent in the examination of pattern 2 final approach performance. The shortness of the crossleg causing task compression, the lack of turn 2 cues, and the absence of course information throughout both turns and the crossleg all combined to degrade pilot performance. The extremely large course error at the onset of the final leg would be reduced if course information were given throughout the profile.

In summary, due to the use of conventional avionics and displays, course navigation problems dominated performance of these curved/segmented approaches. The inclusion of course guidance throughout a curved/segmented approach would alleviate the present course navigation problems. The pilot, however, still may suffer from a lack of azimuth information. Current displays could present adequate tracking information, but do not permit the pilot to readily and accurately determine his position in the terminal area.

APPENDIX A

PARAMETERS RECORDED EVERY 0.2 SECONDS

Pattern Number
Mission Number
Subject Number
File Count

Geographic Altitude
Latitude
Longitude
Position on A-axis (Feet)
Position on B-axis (Feet)
Lateral error from nominal track (Feet)
Vertical error from nominal track (Feet)
N updates per let

IAS minus 140 kts
Indicated airspeed (kts)

Pitch Angle
Roll Angle
Sin of Aircraft Heading
Cosin of Aircraft Heading
Throttle position
Rate of Climb

Wind Speed
Sin of wind direction
Cosin of wind direction

APPENDIX B

CROSS LEG PARAMETERS

PATTERN	CROSSLEG DISTANCE	CROSSLEG FLYING TIME
Pattern 1 (2 NM./45°)	2.8 NM.	70 seconds
Pattern 2 (2 NM./60°)	1.8 NM.	47 seconds
Pattern 3 (4 NM./45°)	4.3 NM.	110 seconds
Pattern 4 (4 NM./60°)	2.9 NM.	74 seconds

APPENDIX C
QUESTIONNAIRES

Post Mission Questionnaire

1. Did the information display provide you with enough data for you to maintain a realistic orientation of your horizontal situation in reference to the runway? Please elaborate.

2. Did you encounter any difficulty in staying within the glide slope plane throughout the profile? Which portions of the profile gave you the most, the lease difficulty? Please discuss.

3. Did the information display data allow you to accurately anticipate and prepare for course changes? Please elaborate.

4. Did the pilot procedures and the information display give you the opportunity to track effectively throughout the approach pattern? Please elaborate.

5. Rate the displays listed below in terms of their importance during the approaches using the attached rating scale.

    (a) Commanded pitch steering   _____
    (b) Commanded bank steering   _____
    (c) Glideslope unprocessed   _____
    (d) CDI (NSI)   _____
    (e) DME   _____
    (f) Bearing pointer   _____
    (g) Azimuth angle indicator (AAI)   _____

6. Rate the instrument configuration you have just used with regard to how effectively it permits you to perform approach patterns. (Circle one)

    (1) Excellent, optimum display
    (2) Very good, can fly easily
    (3) Good, satisfactory to fly
    (4) Satisfactory
    (5) Satisfactory, but some improvements are essential
    (6) Acceptable only if additional information presented
    (7) Cannot be used in the present form

Rating Scale

1. Absolutely essential for safety of flight.

2. Essential, but needed only for secondary information.

3. Useful, but not essential

4. Of some value.

5. Of no value -- or worse.

MLS End of Study Questionnaire

1. Do you feel that the dynamic simulation environment encountered in this experiment permits you to make a valide judgement regarding the feasibility of making landing approaches using each of the given instrumentation configurations in the MLS environment?

2. Comment on the effects and effectiveness of using either processed data or raw data in the MLS environment.

3. Which information display allowed you to maintain the most accurate impression of your horizontal situation? Comment. The least accurate? Comment.

4. Which display gave you the easiest task of staying within the glide slope plane? Comment. The hardest task? Comment.

5. Which display allowed you to follow the horizontal profile most accurately? Least accurately?

6. Rank order the display configurations in order of preference from best to least for flying MLS profiles.

7. Which profiles were easier for you to fly; the ± 2 1/2° or the ± 5° LOC beam? Why?''

8. Which profiles were easier for you to fly; the 45° intercept or the 60° intercept? Why?

9. Which profiles were easier for you to fly; the 2 NM. intercept or the 4 NM. intercept? Why?

10. Comments. Any suggestions for change in instrumentation or simulation.

APPENDIX D
MLS SCORING SYSTEM PARAMETERS

Definition of Terms for MLS Scoring

Variables

N	Leg number.
n_x	Iteration number for Leg N.
A_a, B_b	Coordinates of aircraft position at iteration n_x for N.
H_h	Altitude of aircraft above field elevation at iteration n_x for N.
V_v	Aircraft indicated airspeed at iteration n_x for N.

Constants

$E(N)$, $F(N)$	A (longitudinal axis), B (lateral axis) intercepts for boundary of Leg (N).
$SPHI(N)$ $CPHI(N)$	Sin, Cos of the angle between aircraft track and the A axis.
TGS	Tan of the glide slope.
$C(N)$, $D(N)$	A, B intercept of datum track with Leg (N) boundary
$P(N)$, $Q(N)$	Center of describing circle for datum track turns.
R	Radius of datum track turns.

Error Values

$E(Y)_y$	Lateral error value at iteration n_x for N.
$E(Z)_y$	Vertical error value at iteration n_x for N.
$E(YZ)_y$	Combination error value at iteration n_x for N.
$E(AS)_s$	Airspeed error at iteration n_x for N.

Absolute Average Error (AAE) Terms

AAE_y	Average lateral error for N.
AAE_z	Average vertical error for N.
AAE_{yz}	Average combination error for N.
AAE_{AS}	Average airspeed error for N.

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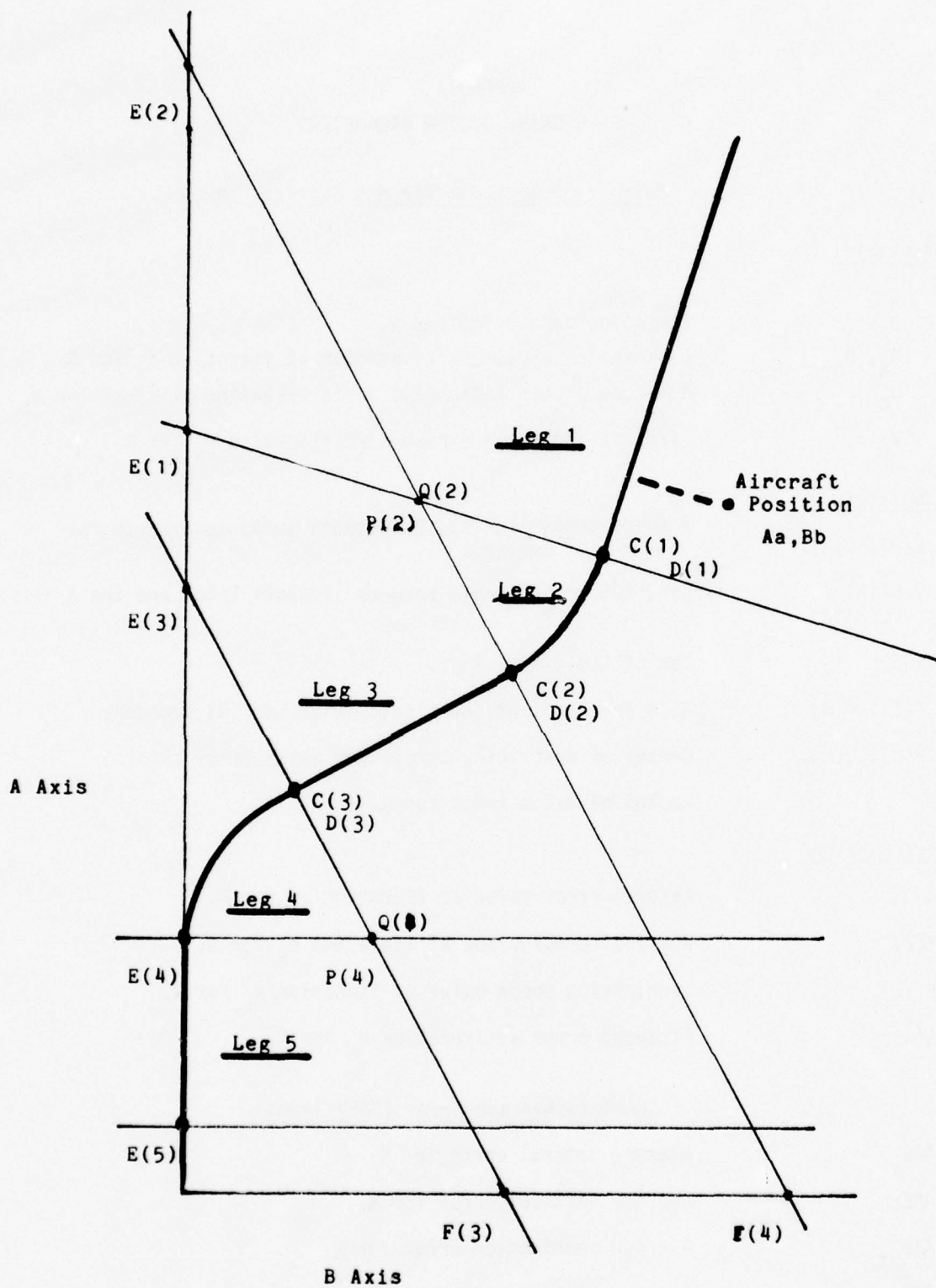
Figure 13
Boundary Conditions

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$\underline{N = 1}$

$$E(Y)_y = CPHI(N) [B_b - D(N)] - SPHI(N) [A_a - C(N)]$$

$$E(Z)_z = Hh - TGS (A_a - 8492)$$

$$E(YZ)_{yz} = \sqrt{E(Y)_y^2 + E(Z)_z^2}$$

$$E(AS)_s = V_v - 140$$

$\underline{N = 2}$

$$E(Y)_y = \sqrt{[A_a - P(N)]^2 + [B_b - Q(N)]^2} - R$$

$$E(Z)_z = H_h - TGS (A_a - 8492)$$

$$E(YZ)_{yz} = \sqrt{E(Y)_y^2 + E(Z)_z^2}$$

$$E(AS)_s = V_v - 140$$

$\underline{N = 3}$

Same as N = 1

$\underline{N = 4}$

$$E(Y)_y = \sqrt{[A_a - P(N)]^2 + [-B_b + Q(N)]^2} - R$$

$$E(Z)_z = H_h - TGS(A_a - 8492)$$

$$E(YZ)_{yz} = \sqrt{E(Y)_y^2 + E(Z)_z^2}$$

$$E(AS)_s = V_v - 140$$

$\underline{N = 5}$

$$E(Y)_y = |B_b|$$

$$E(Z)_z = H_h - TGS (A_a - 8492)$$

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$$E(YZ)_{yz} = \sqrt{E(Y)_y^2 + E(Z)_z^2}$$

$$E(AS)_s = V_v - 140$$

$$\underline{N = 1, 2, 3, 4, \text{ or } 5}$$

$$AAE_y = \frac{\overset{y}{\underset{y = 1}{\Sigma}} |EY_y|}{n}$$

$$AAE_z = \frac{\overset{z}{\underset{z = 1}{\Sigma}} |E(Z)_z|}{n}$$

$$AAE_{yz} = \frac{\overset{yz}{\underset{yz = 1}{\Sigma}} |E(YZ)_{yz}|}{n}$$

$$AAE_{AS} = \frac{\overset{s}{\underset{s = 1}{\Sigma}} |E(AS)_s|}{n}$$

TABLE OF CONSTANTS

	2/45° Route 1	2/60° Route 2	4/45° Route 3	4/60° Route 4
C(1)	33439	27710	52558	43105
C(3)	21990	21971	34150	34131
D(1)	12171	10086	19130	15689
D(3)	1316	2250	1318	2250
P(2)	30977	29249	54097	44644
P(4)	18808	18074	30968	30234
Q(2)	7942	5857	14900.6	11461
Q(4)	4500	4500	4500	4500
R	4500	4500	4500	4500
S	2364	2364	2364	2364
SPHI(1)/CPHI(1)	.3420/.9397	.3420/.9397	.3420/.9397	.3420/.9397
SPHI(3)/CPHI(3)	.7071/.7071	.8660/.5000	.7071/.7071	.8660/.5000
TGS	.0437	.0437	.0437	.0437
E(1)	37869	31381	59521	48817
E(2)	42918	39386	68996	64496
E(3)	23308	25868	35468	38028
E(4)	18808	18074	30968	30234
F(1)	104044	86219	163532	134122
F(2)	42918	22746	68996	37237
F(3)	23308	14935	35468	21956

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APPENDIX E

END OF STUDY QUESTIONNAIRE RESPONSES

1. Do you feel that the dynamic simulation environment encountered in this experiment permits you to make a valid judgement regarding the feasibility of making landing approaches using each of the given instrumentation configurations in the MLS environment?

S-1   Yes, with reservations. In real world flying the final approach is usually complicated by additional outside factors such as ratio calls, turbulance, clear procedures, and a multitude of other distractions which were not (and could not) be in the simulation. These other factors make any kind of a complex approach procedure almost impossible to safely accomplish.

S-2   Yes, but what may be very feasible in one aircraft may be impossible in another. The final roll out ranges flown in this exercise are unrealistic for the B-52 with an average flight crew.

S-3   Yes. Although the T-40 is vastly different than the KC-135 it is possible to compare the two and come up with a valid evaluation of the possibility of flying these approaches in the KC-135.

S-4   Yes, seems like HSI is not modeled in one area. I wanted to try something, see TEST #9 critique. I seem to get into pilot induced oscillations in pitch because of coupling type of actual motion with inertia of control column.

S-5   Yes. This simulator is by far the most realistic I have flown. Actual flight is an obvious factor producing environment which surpasses the simulator, but our data collection from this simulation should afford worthwhile information.

S-6   Yes! I feel that it was more difficult for me coming from the C-5, which has slow control response to the T-40 which has rapid control response. But I seemed to adjust fast and had no real problems.

S-7   No. To be realistic a random wind should be thrown into the test. That is, for each approach there should be a wind from an arbitrary direction at an arbitrary velocity--say between 0-20 knt.

S-8   Basically yes, but your data will be somewhat invalid due to competitive environment leading to use of nonstandard instrument procedures, i.e. exceeding 30° bank during overshooting final. You might get better results if you did not have: (1) run away nose up trim, (2) fuel tank-fuel usage from right tank only, (3) better flight director system, (4) operative bearing pointer, (5) operative reach indicator to aid in lead point determination, (6) fix pilots slip indicator, (7) can't adjust rudder peddles.

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S-10   To some extent, yes--timing is a no-no for course intercepts, it's
        just not the "real world" environment that we, as pilots fly in.

S-11   No. The simulator does not respond as does the aircraft. Simulator
        problems such as fuel balance and rudder trim compounded the
        situation. Simulator monitors did not always give all the criteria
        necessary, i.e. $\pm$ 2-1/2° vs $\pm$ 5° width. Work load is high,
        especially in 45°/2 and 60°/2.

S-12   Yes.

2. Comment on the effect and effectiveness of using either processed data or
    raw data in the MLS environment.

    S-1   As with most flight director systems, blind following of the pitch
            and bank steering bars will most probably cause gross overshoots
            especially at close DME. The HSI and CDI must be constantly monitored
            and personally, I can fly a better approach using only this information.

    S-2   In this situation the processed data was not always helpful and in
            some instances a detriment. I feel this is a characteristic of the
            simulator. Actual airborne experience with processed data using
            ILS is much better than MLS.

    S-3   It is difficult to compare the processed data in the T-40 to the raw
            data because the flight director system in the simulator is not of
            the highest calibre. I think a good flight director system would
            greatly enhance the effectiveness of a MLS approach.

    S-4   CPS and CBS of some value, but are useless in dynamic situations
            (when a pilot may need them most) therefore pilots do not have much
            faith in them.

    S-5   I can fly more precisely with raw data with minimum reference to analog
            info.

    S-6   The pitch steering bar was helpful in maintaining glide slope during
            the crosswind portions of the S turns. The bank steering bar is
            worthless as its washout rate is too slow for this type of approach.
            The bank steering bar is actually a major distraction during the most
            critical parts of the approach.

    S-7   Bank steering bars were not usable. Raw G/S was better than having
            raw G/S and pitch and bank steering bar. The ADI is a must.

    S-8   Those pitch and bank steering bars are not set up at all right.
            They could be a great help but were in the way on this test.

    S-9   During your test, raw data best due to bad flight director system.
            AAI best with $\pm$ 5° CDI travel and timing back up aids. Two NM. final
            too short for safe approach under any conditions.

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S-10   Raw data a must. PSB and BSB are also very important, however, in
        the simulator they, at times, were unusable. Trends in deviation
        were noted first on raw data, which was not continued by PSB and BSB.
        Maybe FDS computer tweeking would help.

S-11   A dampening of the processed data (pitch and bank steering bars) is
        necessary. I preferred raw data in simulator but C-141 and C-5A have
        much improved flight director systems. The CPU-4 is inadequate for
        pitch and bank commands.

S-12   The pitch steering bar provided good command information that is very
        helpful for maintaining glidepath. The bank steering bar, on the
        other hand, presented confusing information during the dynamics of
        changing heading and course, through the DR leg. Raw data (CPI, GPI,
        and DME) Timing is not adequate for lead point determination. An AAI
        or bearing pointer is essential.

3. Which information display allowed you to maintain the most accurate impression
    of your horizontal situation? Comment. The least accurate? Comment.

    S-1   The best combination was the austere system with the AAI. This allows
            real fine course orientation. The worst combination was the analog
            system without the AAI. The lack of radial information caused the
            turn to final to be overshot or undershot because of lack of "lead
            the turn" information. The bank and pitch steering bars only cluttered
            up the presentation and often were misleading.

    S-2   Analog with AAI-Z leg intercept lead points much easier to ascertain;
            austere no AAI-pure guess work most of the time on X leg to final
            intercept.

    S-3   Most accurate was raw data with the AAI (with a good F.D. system
            command bars would help). Least accurate was raw data without the
            AAI especially if this was combined with a $\pm$ 2-1/2° CDI range. Although
            the AAI gave a picture of the azimuth, a bearing pointer to the station
            would be of much greater value. This would not only aid in orientation
            to the station but would be more familiar to the pilots flying the
            approach.

    S-4   AAI during turn to final. CDI on final and radials.

    S-5   Best   Worst

            AAI   Pitch and Bank Steering Bars
            GSI   No AAI
            10° Wide Localizer   5° Wide Localizer

            Lack of bearing pointer negatively affected track maintenance also.

    S-6   The most accurate display consists of an AAI with raw data. The least
            accurate was no AAI and pitch and bank steering bars. Timing to roll
            out in final from crosswind is useless in the real world. You have a
            changing true airspeed and winds to affect your time.

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S-7   AAI, CDI, $\pm$ 5°, GS   CDI $\pm$ 2-1/2°, G/S

This gives you everything you need   Least accurate. Can cause
to fly an approach in all kinds of   large course overshoots,
conditions, i.e. wind or no wind.   especially if you have any
It also helps to prevent large course   kind of winds.
overshoots.

S-8   On track-raw localizer (most), AAI (least) Cross track-AAI (most),
raw localizer (least) accept when it wasn't pegged against the side
of the case.

S-9   Most - raw data plus AAI

S-10   1. Analog AAI-although PSB and BSB did not appear to be very accurate,
if X-check slowed/stagnated, movement of these bars did catch the eye.

2. Austere-completely unacceptable for reasons stated in previous
questionnaire.

S-11   Raw data with AAI. Cross track course is mandatory if this is to be
a precision approach. Timing and heading are inadequate.

S-12   Most   Least

1. CDI (on 10° displacement)   CDS on 5° displacement
2. ADI   No AAI

4. Which display gave you the easiest task of staying within the glide slope plane?
Comment. The hardest task? Comment.

S-1   There was no appreciable difference noted, however, any time the pitch
steering bar wasspresent, it made small corrections on the CDI difficult
to see.

S-2   Analog with AAI - because less attention is given to the intercept lead
point calculation with the AAI present. Austere no AAI the opposite
of the above, is true.

S-3   Austere with AAI. The more orientated in the horizontal plane, the
easier it is to stay on glide slope.

S-4   1. Unprocessed glide slope
2. CPS and CBS

S-5   Best   Worst

GSI with pitch bar and 10° LOC   Pitch and bank combination
5° ILS course

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S-6   Any display with the pitch steering bar makes it easiest to stay on
       glide slope although when combined with an AAI is the easiest because
       it allows you to prepare for the turn to final. No steering bars and
       timing is the most difficult.

S-7   G/S CDI $\pm$ 5° AAI. This gives you more time to concentrate on your G/S
       without worrying about the time on your cross track and worrying about
       overshooting the final approach. The pitch and bank steering bars
       didn't seem like they were giving accurate information. I have seen
       outstanding pitch and bank steering bars on other aircraft.

S-8   Raw G/S and AAI without pitch steering bar. Again, if the pitch
       steering bars are set up right they are very desirable.

S-9   Best - Basic raw data. Least - using flight director - often indicates
       climb with raw data showing high on glide slope. Too much lag in your
       system - others are better - i.e., C-141S.

S-10   Analog and AAI easiest (10°)
       Austere - (5°)

S-11   Raw data - could set the pitch power and heading and remain reasonably
       close.

       Analog - CPU-4 Pitch and bank steering bars to sensitive and raw data
       disagreed many times with analog.

S-12   CDI (10°)
       AAI with pitch steering.

5. Which display allowed you to follow the horizontal profile most accurately?
    Least accurately?

S-1   This answer is the same as number 3 and for the same reasons. Best -
       Austere with AAI. Worst - Analog without AAI.

S-2   Analog with AAI, Austere no AAI.

S-3   Most - Austere with AAI. Least - Analog without AAI. Dead reckoning
       on the cross leg without bearing information to the station was
       difficult. The AAI helped give a picture of where you are. The command
       bars seem to get in the way and at times become confusing.

S-4   1. 2-1/2° CDI
       2. AAI, good only for turn.

S-5   Best - 10° course AAI. Worst - 5° course, no AAI, no bearing pointer.

S-6   No steering bars and an AAI is the most accurate. Steering bars and
       no AAI is the least accurate.

S-7　　CDI $\pm$ 5° AAI was the most accurate
　　　　CDI $\pm$ 2.5° was least accurate.

S-8　　Raw localizer with AAI and $\pm$ 5° CDI

S-9　　Best - raw data. Least - Flight director - very bad lags - should
　　　　also command turn to final. Often indicates turns in wrong
　　　　direction.

S-10　Analog and AAI (10°)
　　　　Austere (5°)

S-11　Raw data - AAI 10° beam width
　　　　Analog - 5° beam width

S-12　10° CDI
　　　　AAI
　　　　FLT DIP

6. Rank order the display configurations in order of preference from best to
   least for flying MLS profiles.

S-1　　1. Austere with AAI
　　　　2. Analog with AAI
　　　　3. Austere without AAI
　　　　4. Analog without AAI

S-2　　Analog with AAI
　　　　Austere with AAI
　　　　Austere no AAI
　　　　Analog no AAI

S-3　　1. Austere with AAI
　　　　2. Analog with AAI
　　　　3. Austere without AAI　　　　Especially with $\pm$ 5° CDI range
　　　　4. Analog without AAI

S-4　　AAI with $\pm$ 5° CDI
　　　　AAI with $\pm$ 2-1/2 CDI
　　　　Austere
　　　　Austere + CPS, CBS

S-5　　1. AAI 10° LOC course, GSI
　　　　2. AAI, 10° LOC, Pitch Bar, GSI
　　　　3. AAI, 10° LOC, Pitch and Bank GSI
　　　　4. AAI 5° LOC, GSI
　　　　5. $\pm$ 5°, GSI, P & B Bars

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S-6   Austere + AAI
        Analog + AAI
        Analog
        Austere

S-7   1. CDI + 5°, AAI, G/S
        2. CDI + 5°, AAI, GS, Pitch and Bank Steering Bars
        3. CDI + 2.5°, AAI, G/S
        4. CDI + 2.5°, AAI, G/S, Pitch and Bank Steering Bars
        5. CDI + 5° G/S
        6. CDI + 5°, G/S, Pitch and Bank Steering BPS

S-8   1. Raw LOC and G/S, AAI, + 5° CDI
        2. Raw LOC and G/S, + 2-1/2° CDI

S-9   Can't due to lack of good flight director system. The data - conclusions
        may be wrongly biased. Plus, give the pilot his other instruments -
        MACH and bearing pointer to get accurate overall picture.

S-10   Analog + AAI
        Austere + AAI
        Austere   About the same - last and unacceptable
        Analog

S-11   1. Raw data - AAI + 5° beamwidth
        2. Raw data - AAI + 2.5° beam width
        3. Analog - AAI + 5° beam width
        4. Analog - AAI + 2.5° beam width
        #'s 3 and 4 would go to 2 and 3 and 2 would go to 4 if the pitch and
        bank steering was dampened.

S-12   1. All items available (CDI + 5°)
        2. All except flt director (CDI + 5°)
        3. All items available (CDI + 2.5°)
        4. All except flt dir (CDI + 2.5°)
        5. No AAI (CDI + 5°)
        6. No AAI for flt DIR (CDI + 5°)
        7. No AAI (CDI + 2.5°)
        8. No AAI (CDI + 2.5°)

7. Which profiles were easier for you to fly; the + 2-1/2° or the + 5° LOC
    beam? Why?

    S-1   I saw little difference in the simulation, however, in real world the
            wind/velocity could give a little trouble with the 2-1/2° beam. Often
            the wind at the start of the approach is significantly different than
            at the low end because of altitude changes. This causes drift changes
            on the approach and as busy as it already is, may overload the pilot.

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S-2   + 5° - earlier reference to the final inbound course is available as
        opposed to an instant indication very close to the glide path.

S-3   + 5° LOC because the bearing and course information was displayed
        earlier allowing more lead time for turns to final. A system that
        switched from + 5° to + 2-1/2° when on final would be best.

S-4   1. When to anticipate turn + 5° easiest.
        2. Easier to keep needle center + 2-1/2° probably most accurate
            [AAI at + 10° and 2-1/2° CDI seems like it might be better.]

S-5   + 5° - Course less touchy, corrections generally easier and more
        precise.

S-6   The + 5° is easier because it is not as precise allowing you to be
        farther off course but actually appearing to be on course.

S-7   + 5° beam. If you didn't have an AAI you could use the CDI for the
        turn to final for all cases except the 60° at two miles. Since most
        pilots are use to flying ILS approaches, they keep a close eye on the
        CDI for case break for the turn to final. Several times I found
        myself using the CDI (+ 5°) instead of the AAI or I used the AAI as
        a backup. Without the AAI you would have to rely on the CDI by itself.
        Timing is not the answer for the cross track segment with winds
        there would be no way you could time it.

S-8   + 5° was easiest because it could be used for intercepting the localizer
        and it wasn't so sensitive when close to LOC transmitter.

S-9   + 5°. Helps determine turn to final.

S-10   + 5° without AAI, some lead points could be computed from info on the
        HSI.

S-11   + 5°. Easier to determine a lead point.

S-12   + 5° LOC beam - less sensitive. The most precise, on the other hand,
        were flown with the + 2-1/2.

8. Which profiles were easier for you to fly; the 45° intercept or the 60°
    intercept? Why?

S-1   45° - Mainly because the lead to final turn is less nd more time
        is available to stabilize on final.

S-2   There was no apparent difference except at the 60° 2 DME which was
        a little quick at times.

S-3   45° intercept much easier to maintain glide slope and easier to
        intercept final and lead the turn. On the 60° itnercept I had to
        change from 700 FPM to 300 FPM to 700 FPM descent rates.

S-4   45° rate of sink changes less easy to anticipate turn to final. Should be little difference if displays are optized.

S-5   45°. Similar changes, slighter lead requirements.

S-6   The 45° are easiest because the less of a turn to final you have to make the easier it is to maintain glide slope and also to roll out on course without overshooting or undershooting. The more drastic a maneuver you make during an approach, the harder the approach is to fly.

S-7   The 45° intercept. The biggest reason is the shorter turn to final. The 60° at 2 miles was really difficult, it was really tough to hit the final approach course on track and on glide path. This is caused by being so close to the station that the G/S and CDI were really sensitive I had several overshoots and a couple of undershoots on this one.

S-8   45°. It took less effort to intercept final localizer.

S-9   45°. More accurate lead points, also all Air Force pilots use 30°-45° for all precision approaches often 15°-30°.

S-10   45°. Not as large a heading change required, threfore X-check did not have as much time to stagnate on ADI, HSI.

S-11   45°. Work load less with 45° than 60° but do not think the turn is as much a factor as is the final distance.

S-12   45° intercepts. Less degrees to turn final glide path more nearly conformed to final glide path. Easier to determine final lead point.

9. Which profiles were easier for you to fly; the 2 NM. intercept or the 4 NM. intercept? Why?

    S-1   The 2 NM. intercept <u>does not</u> give enough time to stabilize the approach especially with a 60° intercept angle. It is much too busy an approach and I doubt that most pilots could consistently complete it successfully in an aircraft.

    S-2   4 NM. More time is available to stabilize on glide path after roll out on glide path turns to final can be made easier at 4 NM.

    S-3   4 NM. The more time you have on final, the easier it is to fly an approach. Also, the system seems to be much more sensitive close in. A large turn under these sensitive conditions is difficult.

    S-4   4 NM. Easier to anticipate with existing displays. Sensitivity of glide slopeind. less. More time to get all settled down for landing.

S-5   4. Same as 9

S-6   The 4 miles are easiest because everything happens slower and you
        have time to judge the approach and correct errors.

S-7   4 NM. intercept. See question 8 for reason

S-8   The 4 NM. Easier to intercept localizer and more time to stabilizer
        on final.

S-9   4 NM. for more accurate airspeed, glide slope course. More time to
        smooth everything out before transition outside to look for runway.

S-10   4. Allows more time for correction to course and GP.

S-11   4 NM. Pilot workload is less. Any deviations could usually at least
        be attempted to be corrected by DH.

S-12   4 NM. Longer time to stabilize on final. Less degrees of lead to final
        required.

10. Comments. Any suggestions for change in instrumentation or simulation?

S-1 1. Some sort of "lead the turn" information is necessary if these approaches
     are to be flown with any degree of accuracy. Perhaps a larger DME leading
     in tenths might help. Also a warning of some sort when approaching the
     the final approach radial.

     2. To obtain the desired accuracy, it is imperative that some sort of
     course information be provided on the crossleg. Without this information
     displayed in a readable form (CDI), these approaches cannot be any more
     accurate than those in use now.

     3. Simplicity is the name of the game. A pilot should never have more
     than one thing to remember at a time. The less actions that require pilot
     attention the better the system.

S-2 The AAI should be double its size for easier reference and the scale should
     be standardized in 5° increments rather than 4°. The bearing pointer
     should be operative and a differentiation determined by experiment to
     ascertain which instrument is most used and most reliable. DME readout
     is not sufficiently refined to permit absolute accuracy when turning to
     the crossleg. A lead point warning indication should be used to warn the
     pilot when he is at the point he selected.

S-3 1. A bearing pointer to the station for orientation and lead points for
     turns to final.

     2. A more accurate DME so the cross wind leg would more accurate.

     3. Less switching during critical phases of flight. The hardest switch
     was resetting the course selector on the CDI.

4. A good flight director system. I think the system on the KC-135 would be able to handle these approaches with little problem (Colins Radio FD-109).

5. Course information on the crossleg would be more in line with the idea of a precision approach than dead reckoning to final approach.

S-4   1. + 10° on AAI instead of + 20°.
        2. Mechanize CDI as per real thing.
        3. Overall best display would be 2-D display of A/C position X, Y relative to pictorial track.

S-5   1. Bearing pointer use is a must.

        2. Turn points designated at a definite DME from radial to "more real world."

        3. AAI - change light green ± 8°) to more discernable color.

        4. Add a fixed reference etching for DME readings

S-6   Forget the cross wind as a track and use turn points on the in-bound radials. It is impossible to track as depicted without a navigation system and trying to do it just throws a lot of luck into the experiment.

S-7   1. Have a 5° LOC for the turn to final; once on final let it switch to 2-1/2°.

        2. The sensitivity on the G/S needs to be reduced for the close in work.

S-8   More effective pitch and bank steering bars. Can't the airspeed indicator be set up to "freeze" also. The pilot's turn needle needs to be repaired to it will work.

S-9   All things I mentioned before, also start pilot straight and level and see how glide slope is intercepted. Don't start straight up level at the intercept point. Try 30° intercept angle for consistency with today's standard and today's experience.

S-10   Have bearing pointer INFORMATION.

        AAI - possibly a tape instrument - flat surfaced.

        Bank steering bar (manual mode) used during DR leg.

        Do not brief subjects on timing; this, I feel, is an unacceptable way of finding a final approach course. However, it is a very good back-up to bearing information. Should be used as an aid, not primary procedure. I would suggest also that during the initial briefing that there be no emphasis placed on competative performance. I see no value of this and it is not what MLS is about. Basically,

what I am saying is that competition has led to trying to beat the
system, get the lines as close to the chart as possible, disregarding
how you get them there. Pilots will know how they did by the data
presented on the FDS, and will be able to adjust accordingly on their
next run.

S-11   Wider localizer beams for final approach course interception. Make
        sure what exact profile is to be flown each time before release to
        include fuel and trim. Have AAI (if used) work relative to CDI
        rather than opposite.

S-12   Each of the profiles could more easily be flown with the availability
        of a bearing pointer.